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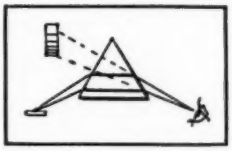

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Journal of the
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Editorial Comment

OPTICAL CONTRIBUTIONS TO NATIONAL DEFENSE

DURING a period of emergency such as the present it is natural for scientifically-minded citizens of a democracy to think occasionally of problems of national defense. During 1917–18, government officials from the President down were overwhelmed with hundreds of thousands of letters from scientists, inventors, and would-be inventors, containing suggestions for confusing the enemy. Usually the less meritorious the suggestion the higher the rank of the official whose attention was demanded for its consideration, the President himself being the usual target for perpetual-motion machines, while a new death-ray required (and frequently got) the attention of at least a Senator. Despite the fact that most of the suggestions thus received were crack-brained and worthless, each idea was painstakingly considered, and a small residue of useful material was found which made profitable the careful scrutinizing of the entire mass.

The government is now as willing to investigate any truly meritorious suggestion for national defense as the most ardent inventor could be eager to impart it. It is not necessary to have recourse to political methods to have an idea considered. Agencies have been set up to pass on all suggestions, and an idea placed in the hands of such an agency will receive more immediate and just as careful consideration as if sent to a high government official.

Persons making suggestions should bear in mind that it may not always be in the public interest to tell an inventor whether or not his contribution is original, is already being investigated, or even, later, whether it has been adopted and developed. The true patriot will be satisfied to know that his suggestion has been put into the proper hands, and that the government will call upon him if he can contribute further.

To assist persons wishing to make suggestions to the government regarding the improvement of existing optical devices, or the invention of new optical devices, of possible value in national defense, the Journal has made arrangements for the transmittal of such material direct to the proper governmental agency. Manuscripts containing such material, not for publication, should be plainly marked with the name and address of the contributor, and should carry the heading "Proposed Contribution to Optics in National Defense." All such suggestions will be held confidential, and due acknowledgment will be made on receipt, both by the Journal and by the governmental agency to which the suggestion is forwarded.

The Twenty-Fifth Annual Meeting
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Rochester, New York,
October 3, 4, and 5,
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Theory of Subtractive Color Photography

III. Four-Color Processes and the Black Printer*

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(Received May 1, 1940)

Two main types of black printer are described—(a) those in which the black printer is only used to increase maximum density; (b) those in which the total gray component of the reproduction is supplied by the black. For practical purposes, the black printer density should be a function of the lowest of the equivalent densities of the three image components when the latter are color-corrected to give an accurate three-color reproduction. Several theoretically possible but somewhat complicated methods of selecting the lowest of three densities are described. The use of infra-red radiation, which is the only previously known method of making a good black printer, is limited in its application, since it depends on accidental or artificially introduced relationships between visual and infra-red brightness. For accurate brightness rendering, the color-corrected three-color separations require further correction by means of a black printer mask.

ALTHOUGH three-colored image components are theoretically sufficient for accurate color reproduction, it is common practice in the field of photomechanical printing to use a fourth printing color, usually black, but sometimes brown or dark blue. The reason for this is twofold. In the first place, the maximum density obtainable in three-color prints on paper is limited. Second, it is difficult to obtain proper color balance in a three-color reproduction of neutral colors, and the use of a black pigment in the reproduction tends to render the grays more nearly neutral. In halftone reproductions, the former is the main reason for the use of a black printer, the densest neutral gray obtainable with ordinary three-color printing inks printed in the proper strength being about 1.2. With continuous-tone processes, such as wash-off relief, the latter reason is more important, since very high densities are often obtainable.

The use of a neutral black as the fourth color will be considered first. It will be assumed that three properly color-corrected color separations have been made, i.e., color separations which will give an accurate reproduction, by the use of ordinary three-color image components, of all colors within the gamut of the original.[1] In order to obtain an accurate reproduction in four colors, it will obviously be necessary to reduce the printing density of all three color-separations at all points where black will print; otherwise, all grays in the reproduction will be too dense.[2]

In the case of three-color reproductions, the problem was simplified by the fact that only one mixture of the three image components could be used to obtain an accurate rendering of any specified color. With the introduction of a fourth image component, there are a large number of possible combinations which can be used. For instance, in the reproduction of a neutral gray, the three colors only may be used, or nothing but black, or any intermediate mixture of four colors between these two extremes.

If suitable corrected negatives could be made easily, the best results would usually be obtained by using the maximum possible quantity of black, and printing not more than two of the three subtractive colors at any one point. A brown, for instance, would be rendered by magenta, yellow, and black in suitable proportions. This will be called the *first type of black printer*. This would have the great advantage that the neutrality of the gray scale would not be dependent on close control of the contrasts of the three color printers.

On the other hand, such printers are difficult to make in practice; the author has, in fact, never

* Communication No. 764 from the Kodak Research Laboratories.

[1] J. A. C. Yule, "Theory of Subtractive Color Photography, I," J. Opt. Soc. Am. **28**, 419–430 (1938).

[2] E. Albert, German Patent 116,538 (1898); E. R. Eaton, U. S. Patent 2,142,437 (1939).

seen a satisfactory print made in this way by photographic means, so that in practice something approaching the *second type of black printer*, in which black is only used to increase the range of neutral grays, is more commonly employed.

There are several theoretically possible methods of making a satisfactory black printer. For the first type of black printer, there is one fundamental requirement to be satisfied; it will be shown that the printing density must be a function of the printing density of the least predominant of the three corrected color printers at any point. The term "least predominant" must, however, be accurately defined. For this purpose, it is desirable to make use of the term "equivalent density" described by R. M. Evans.[3]

The equivalent density of one of the image components in a three-color process is equal to the density obtained by adding sufficient of the other two image components to make a neutral gray. The equivalent density is usually considerably greater than the color density of the image component through its complementary color filter, especially in the case of the yellow and magenta dyes. Provided conditions are chosen so that the requirements for perfect three-color reproduction are satisfied (that is, provided that the laws of additivity and proportionality of densities are satisfied), it is easily shown that the equivalent density is equal to the color density multiplied by a factor given by the equations:

$$Q_C = \frac{1 - M_B Y_G + C_G M_B Y_R + C_B M_R Y_G - C_B Y_R - C_G M_R}{1 - M_B Y_G + M_B Y_R + M_R Y_G - M_R - Y_R}, \tag{1a}$$

$$Q_M = \frac{1 - M_B Y_G + C_G M_B Y_R + C_B M_R Y_G - C_B Y_R - C_G M_R}{1 - Y_R C_B + Y_R C_G + Y_G C_B - Y_G - C_G}, \tag{1b}$$

$$Q_Y = \frac{1 - M_B Y_G + C_G M_B Y_R + C_B M_R Y_G - C_B Y_R - C_G M_R}{1 - C_G M_R + C_G M_B + C_B M_R - C_B - M_B}, \tag{1c}$$

where Q_C, Q_M, and Q_Y are the factors for the cyan, magenta, and yellow images, respectively, and M_B, Y_R, etc., represent the relationships between the densities of the image components through the different filters. For instance,

$$M_B = \frac{\text{blue filter density}}{\text{green filter density}} \text{ of the magenta image,}$$

the denominator being in each case the density through the approximately complementary filter.

The situation may be more easily followed by means of the diagrammatic representation in Fig. 1. Fig. 1A shows the color densities of a few colors through the blue, green, and red filters. In a perfect three-color reproduction, the color densities will be the same as in the original, but the blue filter densities, for instance, will be made up of the blue absorption of all three dyes, as shown in Fig. 1B. In this example, the blue density of the magenta was 50 percent of the green density, and the blue and green densities of the cyan were, respectively, 25 and 50 percent of the red density. In Fig. 1C are shown the color densities of the individual image components of which this image is composed, measured through the complementary filters. The green chosen for this example is of such purity that it can just be matched by a mixture of the yellow and cyan image components only.

These color densities are then converted to equivalent densities by multiplying by the factor Q, as shown at Fig. 1D. By definition, the equivalent densities of the image components in a neutral gray are equal. Regarding each color as a neutral gray with an excess of one or two of the image components added to it, it is obvious that the neutral gray component of any color in the three-color reproduction, that is to say, the maximum amount of the black image component which can replace the other three colors, is equal

[3] R. M. Evans, "A color densitometer for subtractive processes," J. Soc. Mot. Pict. Eng. **31**, 194–201 (1938).

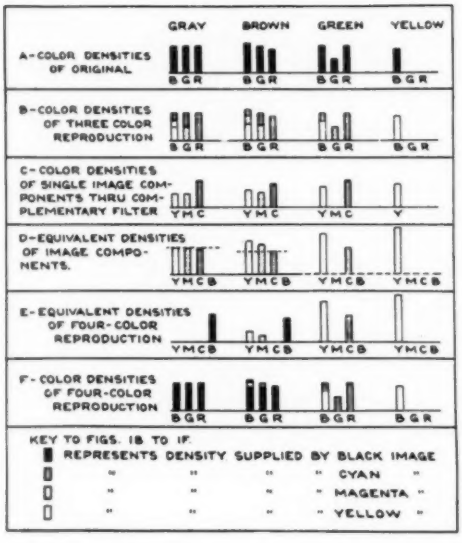
GRAY
BROWN
GREEN
YELLOW
A-COLOR DENSITIES OF ORIGINAL
B-COLOR DENSITIES OF THREE COLOR REPRODUCTION
C-COLOR DENSITIES OF SINGLE IMAGE COMPONENTS THRU COMPLEMENTARY FILTER
D-EQUIVALENT DENSITIES OF IMAGE COMPONENTS.
E-EQUIVALENT DENSITIES OF FOUR-COLOR REPRODUCTION
F-COLOR DENSITIES OF FOUR-COLOR REPRODUCTION
B G R
Y M C
Y M C B
KEY TO FIGS. 1B TO 1F
REPRESENTS DENSITY SUPPLIED BY BLACK IMAGE
" " " " CYAN "
" " " " MAGENTA "
" " " " YELLOW "

FIG. 1. Structure of three- and four-color reproductions.

to the lowest of the equivalent densities of the three image components. This gray component is represented by the dotted line in Fig. 1D. The excess of the other two colors is obtained by subtracting this value from the equivalent densities of the other two image components. To obtain a perfect four-color reproduction of the first type described above, it is only necessary to make a black-and-white print of density equal to this gray component, and to superimpose on this an amount of the three-color image component equal in equivalent density to the excess mentioned above. This is represented in Fig. 1E. The neutral gray consists of black alone; the brown is made up of black, magenta, and yellow; the green, of yellow and cyan with no black; and the yellow, of yellow alone. In Fig. 1F, the contribution which each image component makes to the color densities of the four-color reproduction is shown. The total densities through the three-color filters are identical with the original and with the perfect three-color reproduction.

The fact that it is incorrect to regard the lowest of the three uncorrected color densities as representing the gray component for the purpose of four-color printing is brought out by the green, which requires neither magenta nor black in its reproduction, but which nevertheless has a fairly high density through all three filters. In an accurate reproduction made with properly color-corrected negatives, the green filter density will be supplied by the green absorption of the cyan image component.

The necessity for using equivalent densities instead of color densities is made clear by the brown, in which the magenta has the lowest corrected color density, whereas the cyan has the lowest equivalent density, the latter representing the gray component of the color in terms of these image components. Another important point which is confusing at first sight is that the "gray component," as the term is used above, depends not only on the color under consideration, but also on the image components to be used. This may be illustrated by the reproduction of the green with both ideal and imperfect image components. This color required no magenta in its reproduction, and hence would be said to contain no gray component. Any black added to it could not have been compensated for by the reduction of all three of the colored image components. With ideal image components, a certain amount of magenta as well as cyan and yellow is required in the three-color reproduction; hence, this amount of all three image components may be removed, and black substituted. In other words, in terms of the ideal image components, the green contains a gray component.

It will be seen that the theoretical basis of the first type of black printer is quite simple. Unfortunately, it is exceedingly difficult to reduce it to practice, except when an infra-red negative is satisfactory.

A tentative analysis of some principles which might be applied to the problem is given below.

POSSIBLE METHODS OF MAKING THE IDEAL BLACK PRINTER

The requirement is as follows: The printing density of the ideal black printer at any point should be a function of the lowest of the equivalent densities of the three image components in a perfect three-color reproduction.

The following is equivalent to the above: The printing density at any point should be a function of the lowest density of a set of three color-corrected positives (or the highest density of

three color-corrected negatives) of identical gray scale.

Three basic methods can be cited which we shall call the direct method, the pair method, and the root method.

Direct method

In this case, the least predominant of the three must automatically prevent the others from having any effect. Two theoretically possible applications of the principle are as follows:

(*a*) *Triple-layer halftone.*—A screen negative is made on a triple-layer high contrast emulsion. As in Kodachrome, the lowest layer is sensitive to red, the middle layer to green, and the top layer to blue. This material is either exposed in succession to a set of balanced color-corrected positives, or it is exposed to the original color transparency, in register with a color-correcting mask, through red, green, and blue filters. The exposure is made through a halftone screen in the usual way and developed to a high contrast silver image. The result is shown in Fig. 2. Figure 2A shows the density obtained in the three layers. Figure 2B represents the total density, the sum of the three layers. In Fig. 2C, the dot size obtained in making a print from this negative is given. It will be seen that this is dependent on the size of the dot in the layer having the biggest dots, which corresponds to the positive which has the lowest density, or to the filter through which the masked original has the lowest density. This is exactly what is required for the black printer.

(*b*) *Triple light valve.*—In a photoelectric scanning machine for making corrected color-separation negatives, it would be possible to incorporate a light valve with three elements actuated by the impulses from the red, green, and blue filters, respectively, or to use three light valves in series, as in Fig. 3. The total light passing through the valves would be controlled only by that valve which was most nearly closed.

(*c*) *Variable-time methods.*—The two possibilities discussed above are both variable-size methods, in which the three impulses control the area of light of constant intensity per unit area. It is also a theoretical possibility to allow a stimulus of constant intensity to act for a variable time, the latter being controlled by the greatest or smallest of three densities. Unfortunately, the use of variable-time instead of variable-density negatives does not seem to be within the bounds of practicability; however, in a photoelectric scanning machine, it would be theoretically possible to convert three synchronized variable-amplitude alternating currents corresponding to the red, green, and blue signals, to a single constant-amplitude signal persisting only for a fraction of each cycle, this fraction being determined by the least or greatest of the three original signals.

Pair method

The methods of selecting the least of three quantities directly are very limited in number. By choosing any two of these quantities, selecting the smaller, comparing this one with the third and again selecting the smaller, a few more possibilities are available, although they are too complicated for practical use.

(*a*) *Underexposure method.*—The red filter negative is combined with a 100 percent green filter positive mask. All neutral grays, white, and black will have the same density in the combination, which will be referred to as the standard density. A print is made from the combination on a toeless emulsion, the exposure being adjusted so

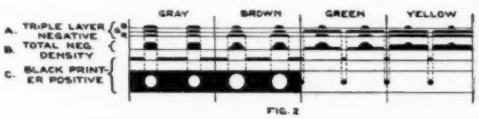

FIG. 2

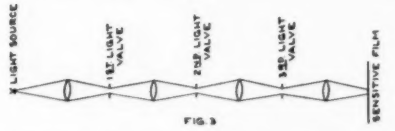

FIG. 3

FIG. 2. Triple-layer halftone method for making black printer.

FIG. 3. Triple light valve method for making black printer.

that densities above the standard density are unrecorded, while those below it are on the straight-line portion of the curve. Since toeless emulsions do not exist, this can only be accomplished by treating with a subtractive reducer. With a gamma of unity in all stages, the density of the print will be equal to the difference between the red and green color densities of the original, when the former is higher, and will be zero when the latter is higher.

The print is then combined with the red filter negative and will have the effect of reducing the color densities at all points where the red density was higher than the green. The corrected color density in the combination is, therefore, equal to the lower of the green and red color densities.

The combination is then combined with the blue filter positive, and the process is repeated. A toeless print is made as before; this is combined with the blue filter negative, and the result is a correct black printer negative, in which the color densities are equal to the lowest of the three-color densities in the three-color separation negatives. The same result can be obtained by using the three separation negatives or positives in any other order.

This description applies to the case of ideal three-color image components, where color correction of the separation negatives is unnecessary. Under practical conditions, color-corrected negatives should be used and corrected color densities substituted for color densities in the discussion just given.

However, there is another and simpler alternative. The color correction may actually be introduced in the course of the process described, without the introduction of any extra steps, at least in the case of the first pair of colors.

Assuming that the red filter negative needs no correction, and that the green filter negative requires correction with a red filter mask, the corrected color densities, D_r' and D_g', are given by the following formulas:[4]

$$D_r' = D_r, \tag{2a}$$

and

$$D_g' = (D_g - mD_r)/(1-m). \tag{2b}$$

The density of the print which is to be used to make the red filter negative must be equal to $D_r' - D_g'$, when this is positive. This is equal to $(D_r - D_g)/(1-m)$, which can be obtained by combining a red filter negative with a green filter positive, both with $\gamma = 1$, and making an underexposed toeless print of $\gamma = 1/(1-m)$ from the combination. This print is then used to mask the red filter negative. The combination thus obtained will be a correct black printer negative for all colors with hues ranging from cyan through green, yellow, red to magenta, but will require further correction by means of a mask made by the use of the blue filter negative, for purples and violets. Complete color correction of the blue filter negative cannot, however, be incorporated in the process. For color correction, it requires a mask made from the green or red filter negative or both; the process to be used consists in combining it with a positive whose density corresponds to the lower of the uncorrected green and red positives.

(*b*) *Photoelectric method.*—It is possible to construct an amplifier which will give an output proportional to the lower of two signals applied simultaneously. A second amplifier of the same type, in which the inputs are the third signal and the output of the first amplifier, will give an output corresponding to the ideal black printer.

Root method

This is a fundamentally different method of selecting the least or greatest of several quantities. It is based on the equation:

$$N = \left(\frac{R^n + G^n + B^n}{a}\right)^{1/n}. \tag{3}$$

When n approaches infinity and a is a number between one and three, N becomes equal to whichever is the largest of R, G, and B. If R, G, and B are the red, green, and blue transmissions, respectively, of the original, N is then equal to the transmission of a perfect black printer to be used in conjunction with ideal three-color inks. In this case, transmissions are used in place of densities, since this equation selects the largest of three quantities. Moreover, it is possible to reduce it to practice when transmissions are used, as will be shown below. However, if n approaches $-\infty$, the equation selects the smallest of the three quantities, and in this case the use of densities would be appropriate.

(*a*) *Triple printing method.*—By printing three high contrast color separation positives in succession onto a low contrast emulsion, an approximation to Eq. (3) may be obtained.

The transmission of a straight-line positive or negative is equal to $T_0 T^\gamma$, where T_0 is the transmission at a point corresponding to zero density in the original, and T^γ is the transmission of the

[4] J. A. C. Yule, "Theory of subtractive color photography, II," J. Opt. Soc. Am. **28**, 481–492 (1938).

original. The total exposure received by a material exposed through this image for time t with light of intensity I is given by tIT_0T^{γ}. The gamma of a negative is assumed to have a negative sign. The total exposure received by an emulsion exposed in succession to three color-separation positives therefore equals $t_1I_1R_0R^{\gamma_1}+t_2I_2G_0G^{\gamma_2}+t_3I_3B_0B^{\gamma_3}$, R_0, G_0, and B_0 being the transmission of the positives at points corresponding to zero density in the original. By suitable exposures, this may be made equal to $K_1(R^{\gamma_1}+G^{\gamma_2}+B^{\gamma_3})$. If the emulsion is developed to a contrast of γ_4, its transmission equals $K_2(R^{\gamma_1}+G^{\gamma_2}+B^{\gamma_3})^{\gamma_4}$, where K_2 is a constant, depending on sensitivity and exposure. This will correspond exactly to Eq. (3), if $\gamma_1=\gamma_2=\gamma_3=1/\gamma_4$, and if it has been correctly exposed. It will not be a perfect black printer, because a gamma approaching infinity cannot be used; however, even when the gammas of the positives only equal 2, the errors are not serious. If the constant K_2 is controlled in the final print so that neutral grays are correctly reproduced, the greatest error will be in pure primary colors, which will have a density of $\gamma_4 \log 3$, or $0.477\gamma_4$ too high. By underexposing the black printer positive, these errors can be distributed equally between the neutral grays and the pure colors, thus halving the maximum errors in the black printer, which will then be only $0.239\gamma_4$ for pure red, green, blue, or gray, and $0.042\gamma_4$ for cyan, magenta, and yellow. A certain range of colors intermediate between the pure colors and neutral grays will contain the correct amount of black.

(*b*) A photoelectric scanning machine using nonlinear amplifiers could theoretically be constructed to comply with this equation.

Infra-red method

Any universally applicable method of making an ideal black printer must depend on the visible color of the original. By utilizing other properties which bear a suitable relationship to the color of the original, such as the infra-red absorption, a satisfactory black printer may be obtained.[5] It happens that most black or gray materials, and of course shadows, have a high infra-red density, whereas strongly colored materials, with the exception of a few inorganic pigments and blue sky, absorb very little infra-red. Utilizing this property, good black printers may be obtained in a large number of cases, and with specially prepared originals, perfect results may be obtained. In this case, the requirement is that the infra-red absorption of each color in the original shall be a function of the equivalent density of the image component which would be least predominant in a three-color reproduction. This method cannot, of course, be applied successfully to the black printer to be used in the reproduction of a three-color photograph, where grays are produced by mixtures of the three image components.

Comparison of methods

It may be of interest to compare the errors of black printer density which may be expected when the various methods are used. In most cases, this may be done by calculation.

In Table I, the color densities of printing inks in a color chart of the type described in Section 2 of this paper[4] given by various methods of making a black printer are shown. Obviously, the only one of the patches which should be recorded in the black printer is the *CMY* (three-color black) patch.

The most common, and probably the oldest, method of making a black printer is from a yellow filter negative. The results obtained are well known to be unsatisfactory, and the reason for this is readily seen from the color densities in column 7. Those colors which require cyan in their reproduction are particularly bad, especially the violet. Albert[6] sought to overcome this by adding a white-light exposure so that the negative received equivalent amounts of blue, green, and red exposure. While this slightly improves blues and violets, it makes all other colors considerably worse, as shown in column 8. Hahn[7] attempted to reduce the amount of black in green colors by combining a red filter mask with the original and giving a green filter exposure with the mask in position, followed by a red filter exposure with no mask. This does not improve blues and violets.

Any method of selecting the least of the color densities through the three filters would give the

[5] A. Murray, Photoengravers' Bulletin **24**, 208 (1935).

[6] E. Albert, German Patent 101,379 (1897).

[7] F. Hahn, U. S. Patent 1,576,118 (1926).

results in column 9. While this is an improvement over the yellow filter method, it is still most unsatisfactory, since the uncorrected color densities are used. However, by substituting corrected color densities (columns 10 and 11) obtained by masking, a very good black printer would be obtained by selecting the lowest of the three (column 12). It would still be imperfect, owing to the imperfections in the color correction of the negatives. The lowest may theoretically be selected by the use of the root method with infinitely high gammas or by the other methods of selection just described. In practice, a fair approximation may be obtained even by the use of the root method with a gamma of 2, as shown in column 13. The results shown were calculated from masks which would give satisfactory results in the three-color printers. By overmasking the three-color printers before selecting the lowest density, good results could be obtained by the use of a less efficient method of selection.

Black Printer for Increasing Maximum Density

The analysis just given refers to the problem of making a black printer of the first type, that is, one in which the whole of the gray component in the reproduction is supplied by the black printer. The second type, in which the only object is to increase the range of the reproduction, is a little more complicated. It would seem reasonable, at a first glance, to use a black printer of the first type, the only change being that the positive would be underexposed so that densities below a certain value remained unrecorded. That this is not a complete solution becomes evident if the reproduction of, say, a deep blue-black is considered, of such a density that the gray component is just equal to the densest three-color neutral gray. Obviously, a correct reproduction would require an excess of cyan over and above that required to produce the densest possible neutral gray; but since the latter already contains the maximum concentration of cyan, this cannot be increased. The only method of obtaining the required hue and saturation with three colors would be by reducing the yellow and magenta; but if this is done, the gray component is insufficient. A correct reproduction could, however, be obtained by the use of black and cyan alone.

This condition will occur whenever the equivalent density, in the corrected color separations, of one of the image components is higher than its equivalent density in maximum concentration. An amount of black equal to the excess must then be substituted for an equivalent amount of the three-color image components, provided this amount is not greater than the gray component of the original color. If it is greater, it means that the color is outside the gamut even of the four-color process.

To make a black printer to meet these requirements, it would be necessary to make a set of three color-corrected positives of equal gray scale contrast on a toeless emulsion and underexposed so that a record would only be obtained where the corrected color density was higher than that of the maximum possible concentration of the corresponding image component. The highest of the three densities of the three positives would then have to be selected, the result being a perfect black printer positive of the second type. This would only be satisfactory provided the original contained no colors outside the gamut of the four-color system. Since originals with colors outside the gamut of the three-color system, but within that of the four-color system, would be the only ones with which this method could be used, and since a black printer corresponding exactly to the second type is not usually required in

Table I. *Column 1—Image components present in color patches. 2—Approximate color of color patches. 3—Color densities of color patches, through Wratten C5 (blue) filter. 4—Color densities of color patches, through Wratten B (green) filter. 5—Color densities of color patches, through Wratten A (red) filter. 6—Color densities of ideal black printer. 7—Yellow filter density. 8—Color densities obtained by Albert's first method. 9—Lowest of the color densities through the three filters. 10—Corrected color densities obtained by a 55 percent red filter mask combined with a green filter negative having 20 percent supplementary red filter exposure. 11—Color densities obtained by a 60 percent green and red filter mask combined with a blue filter negative having 20 percent supplementary green filter exposure. 12—Lowest of the three corrected color densities (columns 5, 10 and 11). 13—Color densities obtained by root method with gamma equal to two, from densities in columns 5, 10 and 11.*

1	2	3	4	5	6	7	8	9	10	11	12	13
Y	Yellow	0.89	0.08	0.01	0	0.05	0.15	0.01	0.14	1.35	0.01	0.16
MY	Red	0.95	0.78	0.04	0	0.27	0.39	0.04	1.07	1.38	0.04	0.29
M	Magenta	0.32	0.76	0.02	0	0.25	0.28	0.02	1.05	0.05	0.02	0.13
CM	Violet	0.51	0.90	0.99	0	0.95	0.75	0.51	0.83	0.02	0.02	0.27
C	Cyan	0.35	0.53	1.08	0	0.72	0.55	0.33	0.02	0.17	0.02	0.18
CY	Green	1.00	0.58	1.08	0	0.76	0.83	0.58	0.11	1.43	0.11	0.36
CMY	Black	1.05	0.95	0.88	0.88	0.96	0.95	0.88	1.02	1.16	0.88	1.05
W	White	0	0	0	0	0	0	0	0	0	0	0

practice, this theoretical process would probably be of no practical value, even if a simple method of reducing it to practice could be worked out. A more satisfactory procedure would be to make a black printer of the first type and underexpose and underdevelop it so that only a certain proportion (a lower proportion in the lower densities) of the total gray component would be recorded in it.

Reduction of Color Printers

Having obtained a satisfactory black printer and a set of three color-corrected separation negatives, it will, of course, be found that if the three-color negatives are printed with the black, the densities of grays are too high in the reproduction. Whether the black printer is ideal or not, the color densities of all three image components should be reduced wherever black is printed. In quantitative terms, it is necessary to reduce the equivalent density of the black printer. This is a practical necessity in wet halftone printing, apart from questions of accurate color reproduction, unless the black is only used in small quantities to improve the densest shadows. It can be shown that the reduction of the color densities may be accomplished by masking, provided the additivity and proportionality laws given in a previous paper are fulfilled. Each corrected color-separation negative or positive is masked by a black printer positive or negative.

When the first type of black printer is to be used, in which the whole of the gray component of every color is to be supplied by the black printer, the solution is very simple. It is obviously necessary to eliminate the record of the gray scale in the color separations; therefore, a 100 percent black printer mask must be used on each one.

When a smaller amount of the three colors is to be replaced by black, it is necessary to allow for the contrast of the black printer in determining the percentage mask to be used.

For a solution of the problem, the tone reproduction curves of the black printer, the color printers, and the corresponding color-corrected negatives must be known. An example is given in Fig. 4. It should be noted that the black printer mask may be used not only to make the necessary reduction to compensate for the black printer,

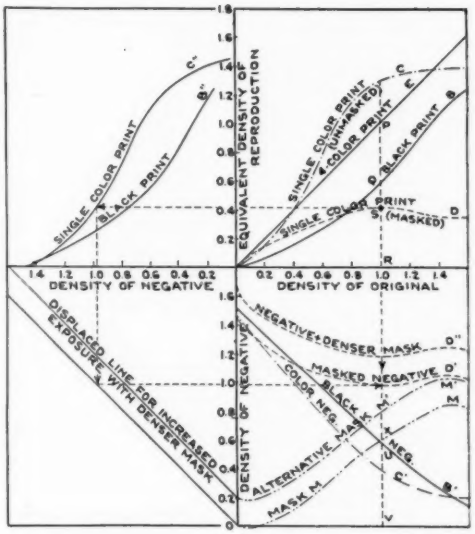

FIG. 4. Correction of tone reproduction by black printer mask.

but also to correct errors of tone reproduction of the gray scale. The data are as follows:

Curves C' and B', respectively, represent one of the color-corrected three-color negatives and the black printer negative plotted against the original; curves C'' and B'' represent the tone reproduction of the color printer and black printer against the negative. From these, the black printer and single-color reproduction curves B and C may be determined. The single-color reproduction curves are plotted in terms of equivalent density.

In the example chosen, it will be seen that the single color-reproduction curve C is not a 45° straight line. This ideal is represented in curve E. Considering a certain density (say, 1.0) in the original, the black printer B supplies a density equivalent to the length of RQ. The density must be brought up to RP by an additional density RS (equal to QP) provided by the color printer. By tracing the point S round the four quadrants of the chart as shown, the negative density T may be found which will give this density in the reproduction. By repeating this for different densities in the original, the curves D and D' may be found, giving, respectively, the required single-color reproduction curve and the negative curve required to produce this. In order to convert the

actual curve C' of the color-corrected negative to curve D', a black printer positive mask is added. The density of this at the point under consideration must be VX. The curve M for the mask is thus obtained. This will be seen to have negative density values in one region. These are eliminated by adding an equal density at all points and increasing the exposure of the print from the masked negative, giving the curve M', the masked negative being represented by D''. The increased exposure may be represented by displacing the 45° line in the third quadrant as shown.

Summarizing, the construction is as follows: Subtract the black printer reproduction densities (curve B) from the 45° straight line E, obtaining the required color printer curve D. From the curves B and C'', construct the required masked negative curve D'. Subtract from this the color-corrected negative curve C', giving the curve M for the black printer mask. Add sufficient density to eliminate negative values, and the mask curve M' and that for the black-masked negative D'' are obtained. By the use of masks and negatives which follow these curves, the ideal gray scale reproduction curve E will be obtained, provided the additivity law holds.

This construction only insures that the gray scale will be properly reproduced. The black printer mask will, of course, have no effect on the pure colors (provided an ideal black printer is used) and will not necessarily correct intermediate colors perfectly unless the curves of the three-color negatives are straight lines and the law of additivity of densities holds. When these conditions are not fulfilled, they may sometimes be realized by substituting effective densities of original and reproduction for actual densities in Fig. 4.

Use of Other Colors Than Black

A common practice is to use a dark blue or dark brown as the fourth printing color. The only change in the requirements in such a case is the modification of the term "equivalent density." As before, all colors may be regarded as consisting of a certain amount of the fourth color together with an excess of not more than two of the three color image components.

As described above, the equivalent density of any one image component was determined by adding the other two until a neutral gray was obtained, then measuring the density. For the present purpose, the other two colors are added until the color matches the fourth image component, in suitable concentration, and the density then measured, if desired, through a color filter. As in the case of the black printer, the printing density of the fourth color is required to be equal to the lowest of the equivalent densities of the three image components adjusted for a three-color reproduction. Methods of obtaining the required fourth color printer are the same as those for the black printer, the only difference being in the contrast of the color-corrected color-separation negatives or positives which must be used as a starting point.

Division of the Spectrum into Four Sections

Four-color printing, where black is not the fourth color, may be regarded in another way. Nearly all naturally occurring colors can be obtained by suitable mixtures of only three image components, each of which absorbs approximately one-third of the spectrum; however, theoretically it would be possible to obtain good reproductions by splitting the spectrum into four or more sections—for instance, red, yellow, green, and blue-violet, with corresponding green-blue, violet, crimson, and yellow image components. Such a system can be more easily color-corrected than the normal three colors and black, and also will include a wider range of colors in its gamut.[8] Some years ago, it was common practice for lithographers to extend this to the use of as many as six colors, but the color correction was done by hand, and the application of masking to so many colors would be too complicated. Three normal colors with the addition of dark blue might conceivably be regarded as a system of this kind, with the dark blue absorbing a very large amount of the other three regions of the spectrum. However, this system is much more closely related to that with three colors and black.

[8] A. Murray, Photoengravers' Bulletin **23**, 13 (1934); C. G. Zander, "The complementary color reproduction process," Penrose's Annual, 9 (1905–1906).

Where a large number of divisions of the spectrum is used instead of the minimum of three, Condition II (spectral sensitivities corresponding to color mixture curves) would no longer have to be considered. The reproduction would duplicate not only the visual appearance of the original, but also its spectral composition; in other words, it might be called an accurate objective reproduction of the original, independent of the properties of the human eye.

ACKNOWLEDGMENT

The writer is indebted to Mr. A. Murray for his interest and assistance, and to Mr. P. S. H. Henry, who suggested some of the theoretical solutions of the problem.

Laminated Sun Glass Lenses

The National Bureau of Standards has recently submitted for acceptance by producers, distributors, and users, two recommended commercial standards for laminated lenses for sun glasses. One of the standards, identified as TS-2913, applies to ground and polished lenses, and the other, identified as TS-2914, applies to blown and drawn lenses.

The recommended commercial standards define laminated lenses as lenses composed of two glass components joined together by one or more laminae. It is stated that sun glass lenses are eye protective (not eye corrective) devices. They are not a substitute for prescription lenses, but may be worn therewith. The visible light transmission shall not exceed 67 percent.

The Recommended Commercial Standard for Ground-and-Polished Laminated Lenses for Sun Glasses requires that the lenses shall be reasonably free from defects visible to the unaided eye, shall have surfaces essentially parallel or of compensated curvatures, with a prismatic effect not to exceed $\frac{1}{8}$ prism diopter; and the focal power shall not exceed $\frac{1}{16}$ diopter in any meridian or as a difference between any two meridians.

A prismatic effect not greater than $\frac{1}{4}$ prism diopter, and focal power not to exceed $\frac{1}{8}$ diopter, is permitted in the Recommended Commercial Standard for Blown and Drawn Laminated Lenses for Sun Glasses.

The purpose of these commercial standards is to provide nationally recognized specifications for laminated sun glass lenses to serve as an assurance and protection to purchasers; to promote fair competition between manufacturers; and to serve as a basis for certification of quality. They were proposed by the Sun Glass Institute, Inc., and have been approved by a Standing Committee of producers, distributors, and users. Promulgation as commercial standards will be made if written acceptances representing a satisfactory volume of the business are received by the National Bureau of Standards.

Mimeographed copies of the recommended commercial standards are available from the National Bureau of Standards, Washington, D. C.

Transmission of Infra-Red Radiation Through Fog

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Boston, Massachusetts

(Received May 3, 1940)

A GENERAL conclusion that seems to have been accepted in the past by those who have studied this subject is that "the intensity of heat rays transmitted through fog showed that, although 7μ rays were slightly less absorbed by fog than visible light, their penetration into fog was too slight to be of practical interest."[1]

Tests reported by H. V. Hayes in 1937[2] indicated that heat rays could penetrate fog and, consequently, were of distinct interest.

The results shown in the Hayes report were so different from those obtained by earlier students of this subject as to raise doubt as to whether the figures obtained in tests made through a fog over a more or less inland body of water could be accepted as applying to fogs at sea where, it was thought, the sizes and character of the suspensoids would be essentially different. Also the Hayes results have been criticized as "incomplete in that they give no quantitative information on the nature of the fogs encountered."

In view of the above criticisms it was decided to repeat the observations over Boston Harbor and to make new and similar tests with the same apparatus virtually at sea and during times of the heaviest fogs found on the coasts of Massachusetts. The place chosen for these latter tests was a very narrow strip of sand projecting into the sea from Chatham, Massachusetts, and known as Monomoy Point.

In preparing for these tests, it was decided that the method selected must be one in which "visibility" was not made the criterion of the atmospheric conditions, as had been the case in most of the investigations made in the past. There are too many factors entering into what has been called "visibility"—which necessarily involves the human eye—to make it possible to thus describe the condition of the atmosphere through which a beam of radiant energy is passing. The visibility of an object depends greatly upon its illumination and upon the contrast of its color with that of the background. Again the human eye has the ability to adjust itself to a sensitivity best suited for the reception of light of different intensities. This characteristic militates against its reliability in seeing a distant light source, especially in times of fog, and more particularly at such times as the fog is more or less illuminated by some other source of light such as the sun, moon or stars.

Again we were satisfied that accurate "quantitative information on the nature of the fogs encountered" cannot be obtained by sampling, i.e., by taking samples of surrounding atmosphere and attempting to determine the number, size and distribution of the droplets of water forming the fog. We were certain that satisfactory tests can be made only when the path of the beam is between a source and a receiver at a considerable distance from each other and at a reasonable height above the surface of the underlying ground or water. Our experience, gained from hundreds of tests, has been that the atmosphere is rarely homogeneous. With a beam of radiation about fifteen hundred feet long and eighteen inches in diameter (the diameter of the reflectors used in our tests) through a nonhomogeneous atmosphere it is extremely improbable that any sample, especially one taken near the ground, would give quantitative information relative to the nature of the atmosphere lying in the path of the beam.

In view of the above, it was decided to place no reliance upon "visibility" nor upon attempts to determine the physical composition of the fog, but to measure quantitively the energy of different portions of the spectrum of the radiant energy which reaches the receiver from the source after passing through a fog-laden atmosphere. It was planned to obtain this division of the spectrum by the use of filters so designed as to separate the spectrum into bands of wave-lengths. Thus one filter would permit virtually only the shorter wave-lengths, i.e., visible and nearly visible, to reach the receiver; a second

[1] E. O. Hulburt, Physics **5**, 101 (1934).
[2] H. V. Hayes, Rev. Sci. Inst. **8**, 342 (1937).

filter would create an intermediate band which would extend from the first band to a third band, which third band would permit only the longer rays to reach the receiver. If the energy reaching the receiver is measured after passing through the atmosphere and through each of these filters, a *standard of maximum transmissibility* would be established for each band in turn. If similar measurements were made in times of a foggy atmosphere, and the energy received by each band were compared with the standard for that band, reliable data would be obtained from which definite knowledge could be obtained as to the relative absorption by the atmosphere of radiation of different wave-lengths.

The receiver used throughout our tests, both in the laboratory and in the field, was the Hayes radiometer.[3] For the tests in the field the radiometer was mounted in front of an 18″ rhodium-faced metal parabolic reflector having a 7.875″ focal length, in such a way that the incoming radiation from the source was reflected by the mirror and fell upon the heat sensitive element of the radiometer. Means were provided whereby a filter could be placed directly in front of the window of the radiometer, the object of the filter being to permit only the desired wave-lengths to impinge upon the active element of the receiver. The mechanical arrangement was such that a filter could be introduced and removed in a few seconds without changing in any way the focusing or orientation of the receiving apparatus. The output of the radiometer-amplifier was connected in many cases with a Grass ink-writing recorder. In other cases a small Weston meter was used to show the output. The time required to insert a filter and to make ten or more records of the output was rarely more than fifteen seconds.

The relative transmissibility of the several filters for a given source was obtained by the use of a spectrometer equipped with a rocksalt prism. The energy was measured by means of a Hayes radiometer. These tests were made in the laboratory, and the path of the beam of radiation was only that required by the spectrometer. Several sources of radiation were used in the course of the tests in the field. The spectra of the different sources varied considerably, and as a consequence it was necessary to plot the energy received throughout the spectrum from each source when each of the several filters had been inserted into the path of the beam. The results of these tests with the different sources and with the three filters are shown diagrammatically directly beneath the curves derived from the results of field tests over the path between the source and the distant receiver.

The three filters used in our tests were: For band I—a water filter with glass faces; for band II—a red sextant glass; for band III—a magnesium oxide filter.

To illustrate the method used in recording the results of tests in the field under various atmospheric conditions Table I is presented.

The readings in column (1) represent the best reception obtained with the various filters and with the same source, over the same range, and at practically the same time. These figures indicate the clearest condition of the atmosphere when the water content was small (or speaking in ordinary terms, when the "*visibility*" was greatest). Columns 3, 5, and 7 were records obtained with the same sending and receiving apparatus over the same range in thicker and thicker weather.

The readings in column (1) were taken, therefore, as the best that could be obtained without a filter and with each filter individually. The figures in column (1) were each taken as the maximum (100 percent of column 2) for the component frequencies arriving at the radiometer. (It must be understood clearly that the differences in the figures recorded on each horizontal line in Table I under the headings "reading" were due entirely to the presence of suspensoids in the path of the beams through the atmosphere.)

TABLE I. *Comparison of energy received by radiometer under various conditions of atmosphere.*

FILTER	1 READING	2 %	3 READING	4 %	5 READING	6 %	7 READING	8 %
No filter	530	100	436	82	400	76	190	36
Water (band I)	26	100	18.6	72	12	46	2	8
Red glass (band II)	255	100	200	78	172	68	87	34
Mg O (band III)	250	100	185	74	160	64	110	44

All of the tests which will be considered here were made over two ranges.

Range 1.—This range was in Boston from a

[3] H. V. Hayes, Rev. Sci. Inst. **7**, 202 (1936).

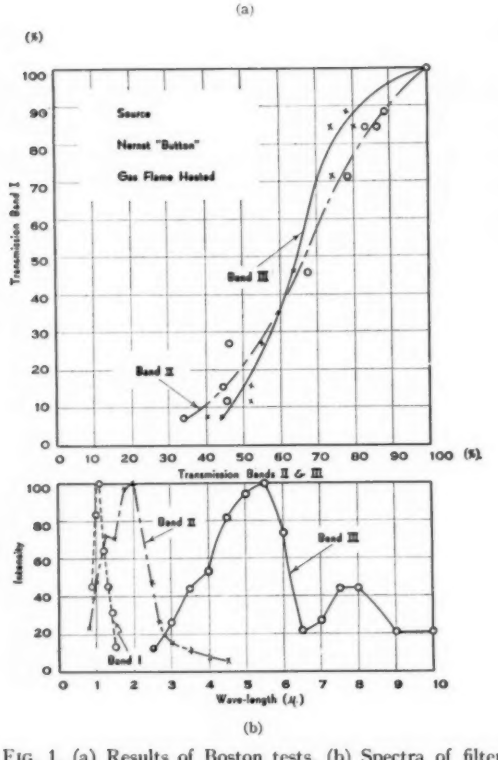

FIG. 1. (a) Results of Boston tests. (b) Spectra of filter bands from hot button of Nernst materials.

window about 75 feet above the ground to the roof of a building about 30 feet above the ground, and about 1500 feet distant. The path of the beam between the stations was almost entirely over a cove in Boston Harbor.

Range 2.—This range was at Chatham, Massachusetts, which location was selected as probably subjected to more and denser sea fogs than can be found elsewhere along the Massachusetts coast. The tests were made on the beach below and to the east of Morris Island which is located about 0.9 of a mile southwest of Chatham Light House. The receiving apparatus was placed at a window of the Chatham Coast Guard Station boathouse about 25 feet above the ground and about 60 feet from high water mark.

The sending station was on a small dune about 1500 feet distant from the receiving station. The dune was about ten feet above the level of the surrounding terrain and about 10 feet from high water mark.

RESULTS OF TESTS AND THEIR INTERPRETATION

Figure 1 shows the results of a number of tests made in Boston in which the source was a small "button" of Nernst materials with a binder of sodium silicate. The button was supported by a platinum wire and was heated by the flame from a small acetylene torch with automatic pressure regulation. Obviously, due to the method which was described above, wherein the observations were recorded in percentages of a standard for

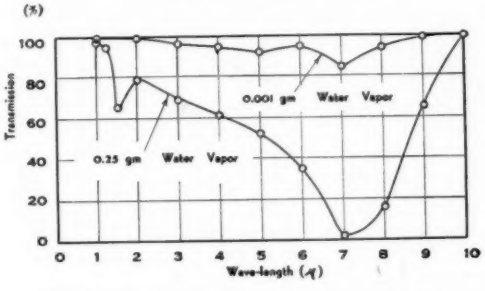

FIG. 2. Effect of water vapor on transmissivity.

each band, if the percentages of transmission for all of the wave bands were the same the plots would be straight lines from the 100 percent point to the origin. Since they are not it is equally obvious that the transmission of band I varies from that of bands II and III. The fact that the transmission of band III in the region from 100 percent to 70 percent is less than that for band I can be explained by the transmission curves of Fig. 2.

Figure 2 shows[4] that when there is little water vapor in the atmosphere, as on a very clear day, the transmission is high for all wave-lengths. However, as the amount of water vapor in the path of the beam of radiation increases, the absorption becomes increasingly more selective until with a fairly large amount of vapor present the transmission for the region between five and twelve microns is approaching a minimum, while the transmission for the shorter waves is still relatively good. Since this condition is the one which necessarily obtains just prior to the formation of fog particles, one would expect a rapid decrease in the transmission of band III over band I until such time as the atmosphere becomes

[4] From Fowle, Smithsonian Miscellaneous Collection, 68, No. 8.

saturated, or nearly so. This explanation is supported by the curve of Fig. 1(a). Band III shows a greater attenuation than band I for the region between 100 percent and 70 percent, after which the attenuation of band I becomes increasingly greater than band III, apparently caused by the selective scattering of the fog particles, until the condition is reached where the transmission for band I is 0 percent while the transmission for band III is between 30 and 40 percent. The same line of reasoning can be applied to band II.

Figure 3(a) shows the results of several tests made in Chatham. The source of radiation in these tests was a 50-cp automobile spotlight bulb. The lower set of curves shows the spectral intensities of this source after its radiation has passed through each of the three filters. In these tests there is practically no difference between the transmission of bands I and II, while there is a great difference between bands I and III. The reason becomes apparent on inspection of Fig. 3(b). Here it is shown that the characteristics of

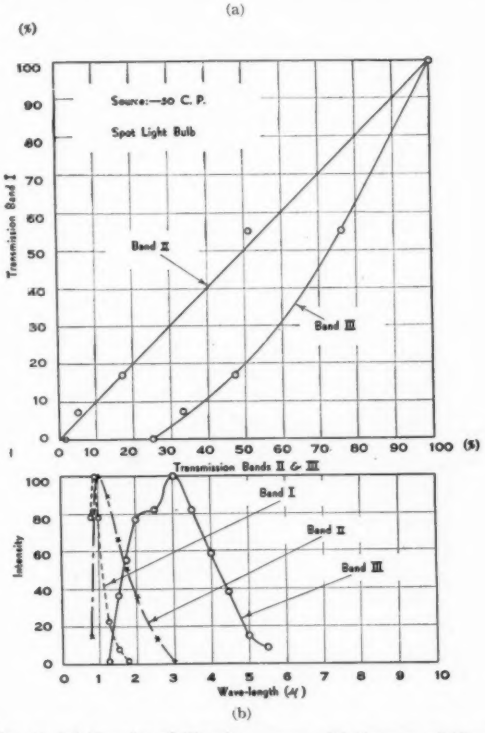

FIG. 3. (a) Results of Chatham tests. (b) Spectra of filter bands from 50-cp spotlight bulb.

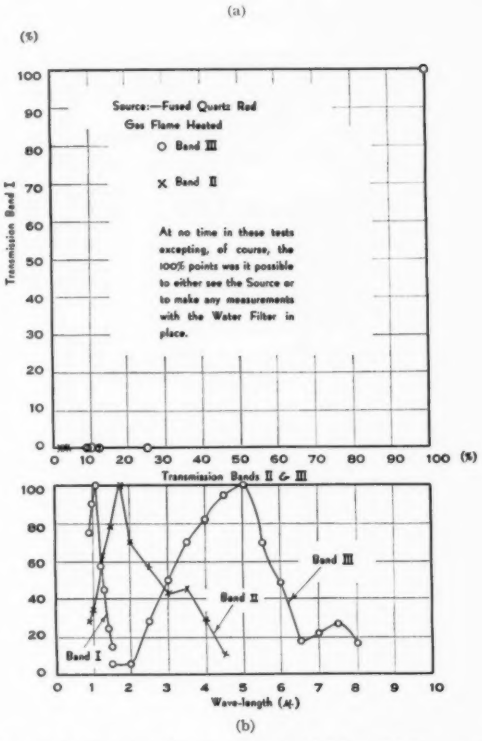
(a)
(%)
Source:—Fused Quartz Rod
Gas Flame Heated
○ Band III
× Band II
At no time in these tests excepting, of course, the 100% points was it possible to either see the Source or to make any measurements with the Water Filter in place.
Transmission Band I
Transmission Bands II & III
(%)
Band III
Band II
Band I
Wave-length (μ)
(b)

FIG. 4. (a) Results of tests through thick fog. (b) Spectra of filter bands from hot fused quartz.

bands I and II are similar but that neither resembles band III. This band of Fig. 3(a) may be compared with band II of Fig. 1(a) to which it is not dissimilar.

The source used at the time of the tests recorded on Fig. 4(a) was a small piece of fused quartz heated by an acetylene flame. The spectral intensity of this source after its radiation had passed through each of the filters is shown on Fig. 4(b). Figure 4(a) shows several points for the transmission of bands II and III when it was not possible to measure any of the energy in band I. However, the grouping of the observations that were obtained reveals that the transmission for band III was greater than for band II.

Figure 5(a) shows the relative transmission for several sources used in tests at Boston and at Chatham and Fig. 5(b) shows the characteristics of the sources derived as explained above. As before, the transmission obtained from the source which was richest in the shorter rays has been

reduced. Special attention is called to the fact that, for similar sources, the curves are similar regardless of whether the tests were made within a harbor, as in Boston, or substantially at sea as in Chatham.

It must be realized that band I was made the basis of comparison as it most nearly represents the visible portion of the spectrum plus about that to which the photoelectric cell is responsive. Thus Fig. 1(a) shows that, when the atmosphere was so laden with moisture that the intensity of the radiation within band I was only 36 percent of that which had been received on the clearest day, the intensity of the radiation of the rays of longer wave-lengths, i.e., those in bands II and III, at the same time and under the same conditions was about 60 percent of that found on the clearest day. Likewise, when the radiation within band I was so small as to make reliable readings impossible, the received radiation of band II and band III was about 34 percent and 44 percent of that which had been received under similar atmospheric conditions.

The only conclusion that can be reached from the above figures is that: *Of the radiation from a hot source the longer rays suffer less attenuation in passing through a fog than the shorter visible or nearly visible rays.*

Our conclusion differs so radically from that of others who have studied this subject that some explanation seems to be required.

Apart from the method employed by us in dividing the spectrum of the radiation into "bands" and comparing the energies received in the several bands practically simultaneously at times of different atmospheric conditions, we attribute to the receiver used by us a sensitivity, accuracy, and rapidity of operation which probably has never been possible before.

Again the receiver used in these tests is responsive to radiation of all wave-lengths from 0.4μ to about 15μ. The photoelectric cell, which has been used in some past studies of this subject, responds only to wave-lengths shorter than about 1.2μ. This means that the photoelectric cell was capable of measuring only the radiation included within our band I. It was incapable of responding to waves longer than 1.2μ, the very waves which are effective when the path of radiation is through a fog.

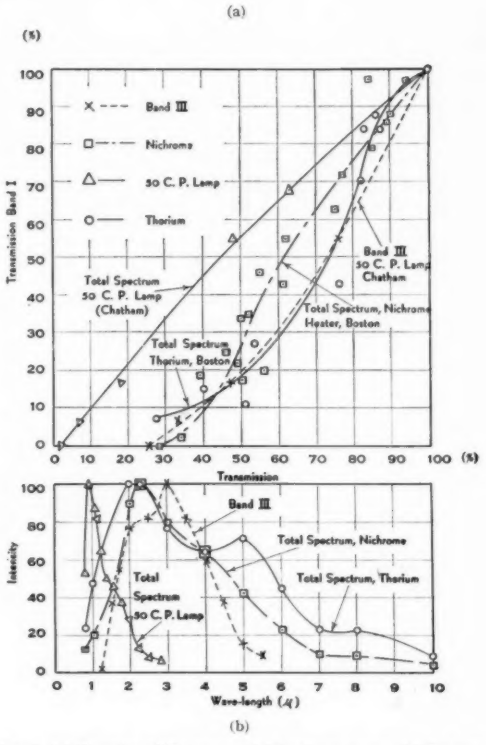

FIG. 5. (a) Results of Boston and Chatham tests. (b) Spectra of above sources.

The receiver used in many former studies was a thermocouple associated with a reflector. The combination of a thermocouple and parabolic reflector tends to give the thermocouple a very limited field of view. One factor influencing the field of view is the size of the active area of the receiver. The area of the window of the Hayes radiometer is about 126 mm², while the probable active area of the thermocouples used in past tests was not larger than 6 mm². The result of these dimensional differences gives the Hayes radiometer a wider field of view than was probably ever attained with the apparatus used by earlier experimenters except Langmuir and Westendorp,[5] who used a special *photoelectric* cell with a large active surface to obtain the desired wide field of view. However, the photoelectric cell used by them could respond to only a portion of the radiation scattered by the fog, as their

[5] I. Langmuir and W. F. Westendorp, Physics **1**, 273 (1931).

receiver was unresponsive to the longer scattered rays. Assuming that their photo-cell had the same field of view as that of the Hayes radiometer, much of the scattered radiation which was lost by their photo-cell would have actuated the Hayes radiometer and increased the amount of energy received. We are satisfied that, if the distance between the source and the receiver is not too short, and if the path of the beam is not too near the ground (as was the case with some of the earlier experimenters), much of the scattered energy of the longer waves would be picked up by the receiver and added to the energy of the direct beam.

A test was made by us to see if the above would be confirmed. The distance between the sender and receiver at Chatham was about 1500 feet. At a point about halfway between the transmitting and receiving stations a post was erected so that a board could be mounted upon it at will. The board was 26 inches square (area of about 4.7 square feet). The cross-sectional area of the direct beam between the two 18-inch reflectors was less than 2 square feet. Our experiments showed that, when the atmosphere was clear, the interposition of the board across the beam at the post completely blocked the radiation so that the radiometer showed no output. However, when the experiment was repeated during a fog, the energy received with the board across the beam was from ten to twenty percent of that received with the uninterrupted beam, this in spite of the fact that the area of the board was more than twice the area of the beam. Obviously, if the board had been only 18 inches in diameter or just large enough to block the beam itself and no more, a larger percentage of the radiant energy would have been found to be coming around it. It is evident from the above that, if the direct beam is near the ground or if the distance between the transmitter and receiver is small, there would be less energy from the scattered radiation that would reach the receiver.

From the facts and figures given above we have reached the following conclusions:

(1) It is possible, by the use of proper equipment, to detect and measure the energy of infra-red rays 3μ and more in length through the worst conditions of atmosphere and ambient illuminations to distances considerably greater than the limits of "visibility."

(2) A large part of the energy received from such sources as were used in the above tests is composed of energy scattered by the fog.

(3) The device developed and used to receive and measure the energy reaching the receiving station under all atmospheric conditions fulfills all requirements now known to us.

Method for Obtaining Long Optical Paths

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(Received June 2, 1940)

WHILE studying the absorption spectra of certain liquids, and gases at high pressures, it became necessary to go to very thick layers of the substances under investigation. Many of the methods previously described for obtaining long optical paths could not be employed due to the fact that the substances being studied were available only in columns of restricted length. A simple apparatus was devised finally by means of which an absorption spectrum, for a path length of several hundred feet, of a substance confined in a limited space, could be obtained with a relatively short exposure time. A brief description of the optical system evolved is given here, accompanied by a series of photographs of actual light paths illustrating several variations of the system which were used under special experimental conditions.

The general experimental arrangement is indicated in Fig. 1, which is a schematic diagram of one modification of the optical system. The positions of the various optical parts were determined roughly in the following manner. The spherical mirror M_3 was placed at one end of the tube containing the absorbing medium in such a way that two plane mirrors M_1 and M_2, situated at the other end of the tube, were at the center of curvature of M_3. A horizontal beam of light from the source S was condensed by the lens L and reflected by a small plane mirror M in a direction designated by beam A in Fig. 1. Successive reflections of the beam at M_3, M_2, M_1 and again at M_3, gave rise to the beams B, C, D as shown in the diagram. The light emerged in a horizontal direction after reflection at the upper part of M_1 and was focused on the slit of a spectrograph. All mirrors used were front-surfaced with evaporated films of aluminum or silver and were completely immersed in the absorbing medium. Regarding the finer adjustment of the apparatus, it was found that when the longest possible path lengths were desired, best results could be obtained by rotating either M_1 or M_2 about a horizontal axis until the portions of the beams between the two mirrors M_1 and M_2 were parallel to one another as shown in Fig. 7a. Under these conditions it is obvious that the angle between M_1 and M_2 is slightly less than a right angle.

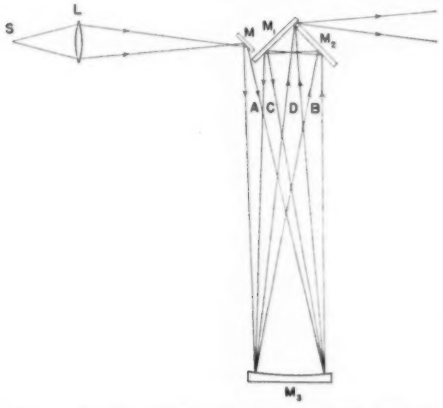
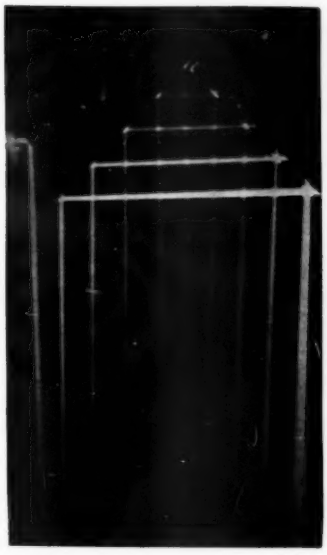


FIG. 1. Schematic diagram of one modification of the optical system.

An abstract of some recent work of Kratz and Mack[1] gives a method for obtaining a long optical path in a limited space by the use of a truncated totally reflecting prism and a spherical mirror. A somewhat similar arrangement, involving the use of a 90° totally reflecting prism, was tried out during the present work. However, it was considered advantageous to replace the prism by the mirrors M_1 and M_2, for the following reasons—

I. When a prism is used, not more than one beam of the group traversing the tube will enter the long face of the prism at normal incidence. A ray striking this surface obliquely from without will give rise to a reflected ray at the glass surface which may travel back and forth between M_3 and the prism. Also, because of multiple reflections within the prism, other extraneous beams will originate there which cannot, without difficulty, be separated or distinguished from the desired beam.

[1] Kratz and Mack, Phys. Rev. **57**, 1059A (1940).



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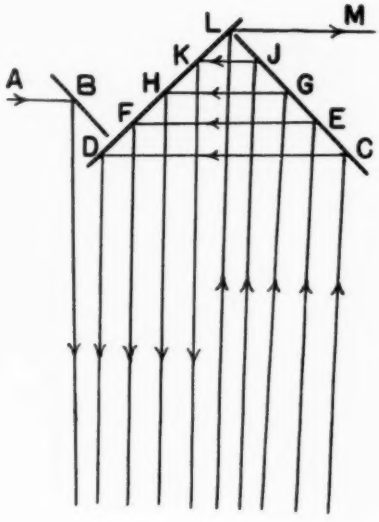

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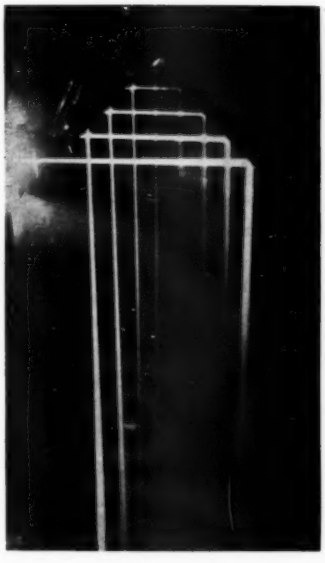
FIG. 2.



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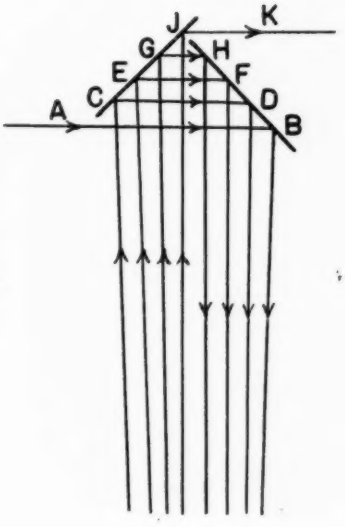

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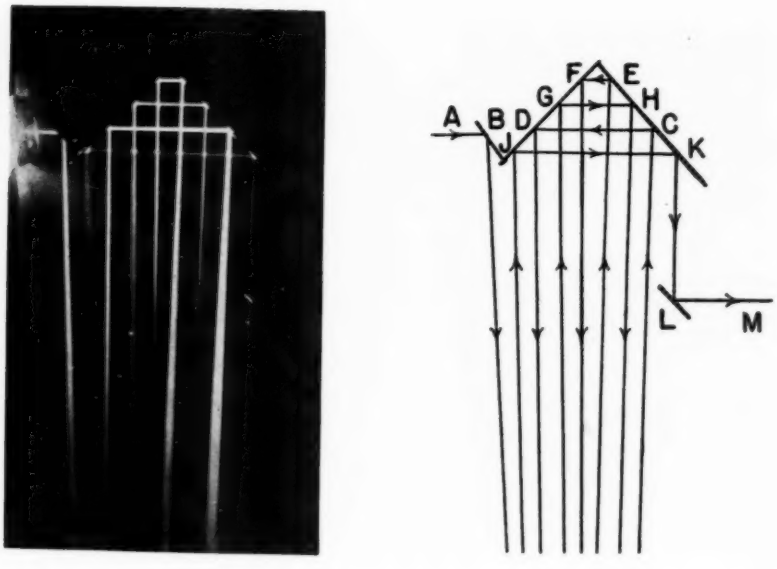
FIG. 3.



a b

FIG. 4.

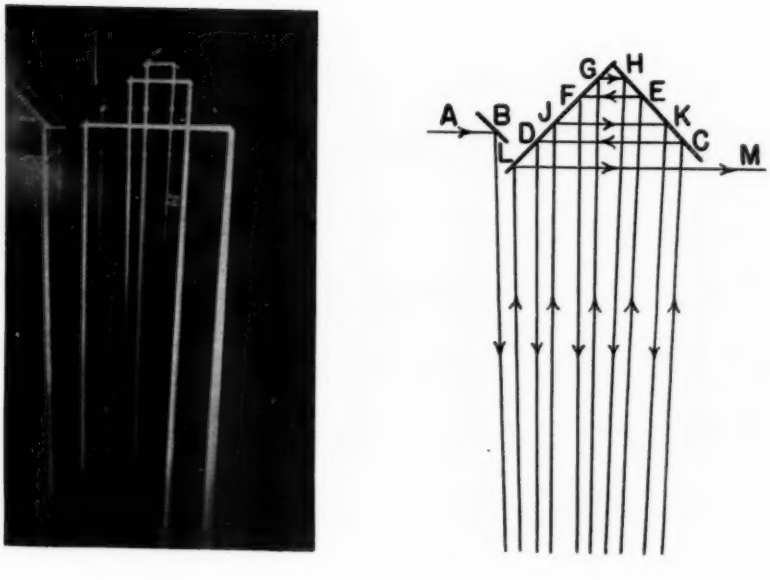


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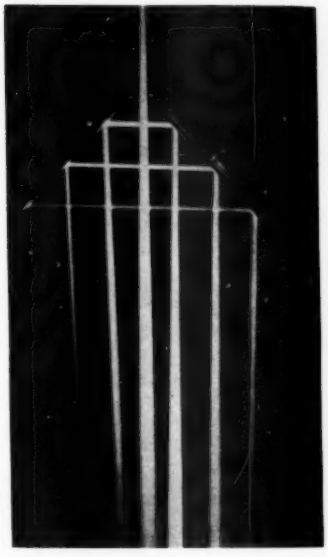
FIG. 5.



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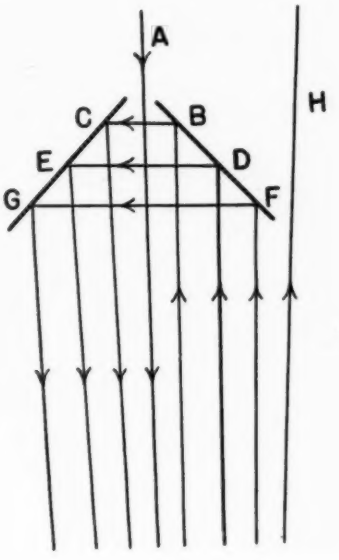

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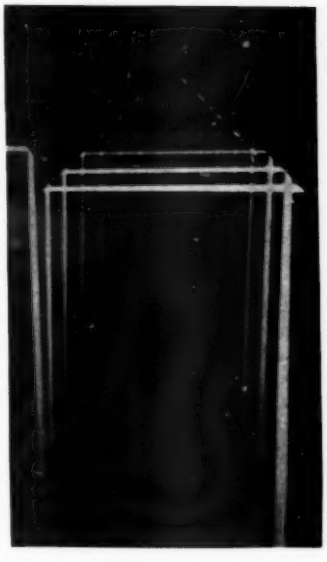
FIG. 6.



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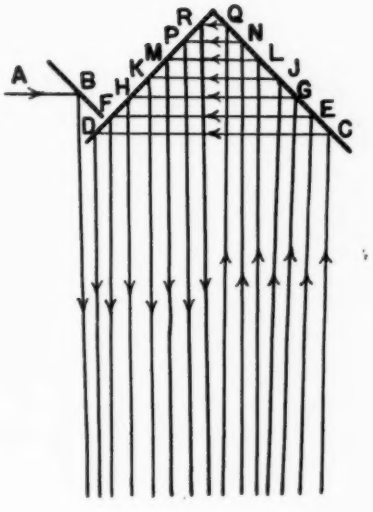

b

FIG. 7.

II. For best results, the angle of the prism, or the equivalent angle between the mirrors M_1 and M_2, is dependent on the radius of curvature of the spherical mirror. When mirrors are employed the required angle for a given spherical mirror may be obtained readily. Concerning the extent of the variation of this angle, it was found that for a particular experimental arrangement where a series of mirrors of radii of curvature ranging from 8 in. to 6 ft. were used, the angle between M_1 and M_2 varied from 87° 45′ to 89° 41′.

III. Under certain conditions better results may be obtained by reducing the length of one of the plane reflecting surfaces. When employing mirrors, this may be done as illustrated in Fig. 5a by overlapping one mirror with the other.

IV. For a given spherical mirror one may obtain quickly, a wide range of path lengths, without moving spectrograph, tube or source, by the rotation of either M_1 or M_2 about its axis, accompanied by an adjustment of M_3 which is not particularly critical.

V. Some of the modifications of the optical system exhibited in the photographs could not be obtained with a prism without considerable difficulty.

Figures 2a–7a show the actual paths of rays in the vicinity of the plane mirrors for a number of variations of the optical system. These plates were obtained by photographing the light scattered by smoke particles introduced in the paths of the beams. The central rays of the beams are shown in the diagrams accompanying the plates, the arrows indicating the directions of the rays. If we suppose that the oblique rays converge at a point 0 on the spherical mirror, then the path in each case may be written in terms of the letters in the diagrams. Thus, in Fig. 4b, the light follows the path *ABOCDOEFOGHIOJKLM*. For the photographs reproduced here, the spherical mirror had a radius of curvature of 5 ft., and the plane mirrors, M_1 and M_2 were 2 in. long and 1 in. wide. A carbon arc, drawing 12 amp. in a 110-volt, d.c. circuit, served as a source of light.

Figure 2a shows a system, in which there are 10 traversals of the tube and where the absorption path is approximately 50 ft. in length. Figure 3a gives a modification of this method in which the small mirror M is eliminated, the initial beam striking M_2. It may be noted that, for the first two methods, the reflections at the plane mirrors M_1 and M_2 after successive traversals of the tube form a series approaching the junction of M_1 and M_2 and emerging there. Figures 4a and 5a show variations of a system in which the series of reflections at the plane mirrors approaches the junction, crosses over and then recedes from the junction. In Fig. 4a a small mirror at L is used to deflect the final beam coming from the outer edge of M_2, while in Fig. 5a this mirror is eliminated by moving M_2 in its plane so that it overlaps M_1 at the junction, and the emergent ray is reflected from M_1. In Fig. 6a the initial beam enters between the two plane mirrors and after a series of reflections which approach the edges, the emergent beam is reflected from the spherical mirror to the spectrograph. Fig. 7a shows the pattern obtained when the light traversed the tube 15 times. The final beam could be reflected out from the center of the group by means of a small mirror. As may be expected, it is difficult to obtain a photograph of a larger number of traversals due to the fact that the intensity of the light along the path diminishes rapidly as it is scattered by the smoke particles.

In general, one sees that for every two traversals of the tube there are three reflections at the mirrored surfaces, one being at almost normal incidence, and two at approximately 45° incidence. In one case with a mirror of 85 cm radius of curvature 37 traversals were obtained without undue difficulty. With a mirror of longer radius of curvature an even greater number of traversals could be obtained. It was found that the above methods could be employed equally well with the absorption tube in either a horizontal or vertical position. The system may be used to advantage also in light scattering experiments and in the determination of the Verdet constants of gases and liquids.

The latter part of this work was carried out at the University of California and the authors are indebted to the Physics Department of that institution for the use of its facilities. Thanks are due particularly to Professors Birge, Brode, Jenkins and White for their kindness in providing special equipment.

Photoelectric Measurement of Scale Marks and Spectrum Lines

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George Eastman Research Laboratories, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received May 29, 1940)

A new type of all-electric balancing network for photometric purposes is described, with which a single phototube or electron multiplier can be used to locate rapidly the center of a scale mark or spectrum line. This device is now in use on two automatic measuring engines, and is found to give results more reproducible than those involving setting by eye. It is far simpler to adjust and to use than the balanced-cell method previously described. As the enlarged image of a line passes at uniform speed across a slit behind which the multiplier is placed, the variation in light intensity produces a variable output current. The resulting voltage is applied after amplification to a delay network designed to give uniform delay and attenuation to all signals of frequency between 0 and 200 cycles per second. Input and output of this network are combined in phase which is opposite except for the delay, so that the voltage at any instant is balanced against the voltage produced 13 milliseconds previously. Thus, with proper mechanical delay, densities at points on a plate separated by as little as 20 microns can be compared, and a sharp signal is obtained at a position corresponding to the passage of the peak of a line across the slit. This pulse is used to fire a stroboscopic lamp which records instantaneously the reading of a dial which measures the position of the plate. Plates are usually scanned at 4 mm per second, and the positions of as many as 4000 lines can be recorded to within 1 micron or less in 120 seconds.

AUTOMATIC length-measuring engines of types previously described[1, 2] have been in use for several years, and have been improved until their operation is now practically routine. More than twenty million measurements have been made with the two engines now available, and in their present form they are found by test to give results more reproducible and precise than those obtained with ordinary comparators by hand-and-eye methods of setting. Mechanical difficulties were practically eliminated in the second model,[2] and this and the reconstructed first model have now been provided with a new device for automatic locating of lines which avoids limitations inherent in the original optical method. Balancing of the photoelectric system is no longer required, the scanning disk has been eliminated, and the electrical system has been greatly simplified.

In the photoelectric method of determination of the position of a line maximum (called for simplicity a "maximum picker") which was first used, a 30-fold-enlarged image of the plate being measured was moved across a triple slit during measurement. Behind each section of the slit was a photo-tube. The output of the central phototube was amplified and recorded on motion picture film with an oscillograph, to give a density trace of the spectrum plate or transparent scale being measured. The two outer photo-tubes, which received light passing through the plate at positions separated by a properly chosen resolution distance, were connected in opposition, and whenever their combined output fell to zero a maximum or minimum of density was indicated. This zero voltage triggered a flash of light which photographed, on the same film as the density trace, the reading of a wave-length dial. For satisfactory operation it was necessary to balance the two outer photo-tubes to within a few tenths of a percent over a range of intensities of 1 to 1000—a delicate operation requiring repetition every few hours. Further, a.c. amplification was needed to give the necessary degree of stability, and on account of the high input impedance of the photoelectric circuit the only practical way of obtaining a.c. was to use a light chopper. To attain the speed of measurement desired it was necessary to produce 5000 light pulses of high intensity per second.

Recent improvements in electron multipliers suggested their use to eliminate need for external high gain amplifiers and a light chopper. However, two multipliers would be even more difficult to balance than two photo-tubes, and it seemed desirable to devise an all-electric "maximum picker" which would operate by electrical balance instead of by electro-optical balance.

[1] G. R. Harrison, J. Opt. Soc. Am. **25**, 169 (1935).
[2] G. R. Harrison, Rev. Sci. Inst. **9**, 15 (1938).

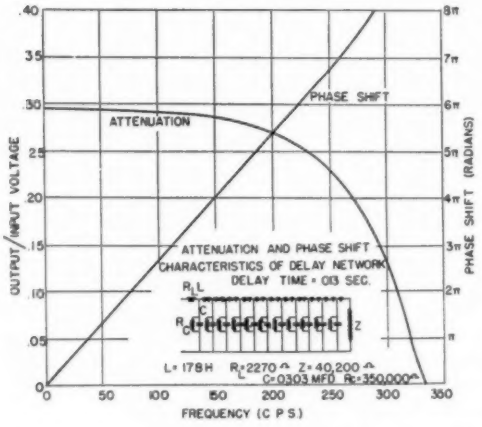

FIG. 1. Curves showing the attenuation and phase shift characteristics of the delay network used for photometric balancing with a single photo-cell or electron multiplier.

Accordingly, an electrical network was designed to delay by 0.013 second any signal which could be composed of frequencies between 0 and 200 cycles, with delay and attenuation practically uniform over the frequency range. Current from a multiplier placed behind a single microphotometer slit is sent through such a network, and the difference between the output voltage of the network and the original voltage from the multiplier is applied to a d.c. amplifier. When this voltage difference becomes zero during measurement of a plate which is being scanned at constant velocity, a maximum or minimum of plate density has passed across the slit of the comparator 0.0065 second previously.

Figure 1 shows the design and behavior characteristics of the delay network, which is seen to have fairly uniform attenuation, and phase shift proportional to frequency, between 0 and 200 cycles.

Figure 2 contains a diagram of the circuit used to control the flashing of the argon light which illuminates the wave-length dial for a few microseconds whenever a density maximum is passed. Only three of the eleven sections of the delay network are shown. Meters, power supplies, cathode-ray tubes (one for recording and one for monitoring), switches, and safety relays are not shown in this diagram. Batteries are used for plate and screen supplies because of the stringent requirement that the noise level be kept low in all main signal circuits. In many cases, however, the tubes could be operated on reduced voltages, so that 45-volt batteries sufficed. The 11-stage electron multiplier, of the electrostatic focusing type, is connected so that the electron current flowing into the last emitter (rather than the

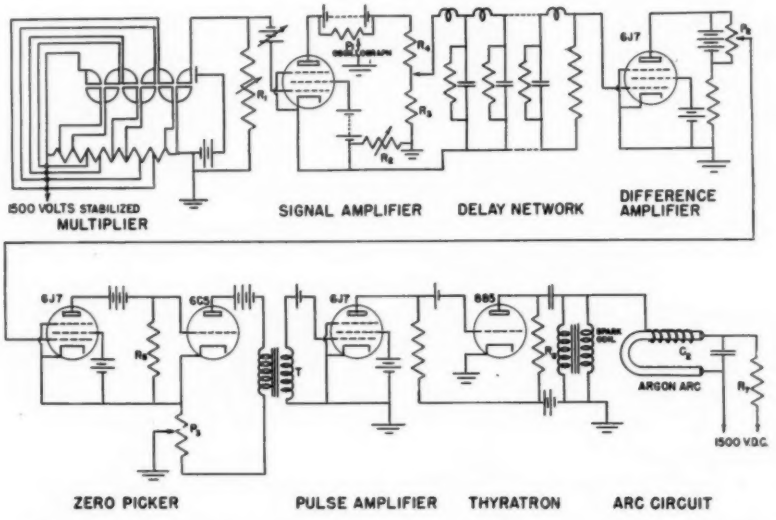

FIG. 2. Complete circuit for recording the position of the peak of a spectrum line or a scale mark. The argon lamp gives a single flash of a few microseconds duration whenever the light intensity falling on the electron multiplier reaches a minimum value.

current flowing into the collector) is used to drive the amplifier. This is necessary because of the grounding requirements in the amplifier circuit. The resistance R_1 varies the signal output from the multiplier; a battery biases the amplifier to the proper point on its characteristic, and at the same time bucks out the additional voltage across R_1 due to the dark current in the multiplier, which may be a considerable part of the maximum signal current. The recording and monitoring cathode-ray oscillographs receive their signal voltages from the drop across the plate load resistor R_4+R_3. P_1 sets the zero point of the spot on the cathode-ray tubes.

The delay network attenuates its output signal to 29 percent of the input. In order to subtract output signal from an input signal of the same amplitude, R_2 is set so that

$$R_2/(R_2+R_3)=0.29.$$

Then the grid of the tube in the difference amplifier receives a signal which is equal to the difference between the delayed and undelayed signals, these having been adjusted to have the same amplitude.

The "zero-picker" consists of a two-tube d.c. amplifier with feedback. The connection used results in an unstable circuit, such that no current flows in the second tube until the grid voltage on the first reaches a certain minimum value; then the current starts to flow in the second, and feeds back through P_3 into the grid of the first until the circuit "runs away." The current in the plate circuit then reaches a maximum which will not change with further increase of the voltage on the grid of the first tube. If this grid voltage is reduced, a point can be found where the plate current in the second tube will come back to zero in a similar instantaneous manner. These sudden changes of current are differentiated by means of transformer T in the plate circuit of the second tube, the result being a positive and a negative pulse, as shown in Fig. 3c. By choosing transformer T with care the duration of this pulse can be reduced to less than 0.0002 second.

Potentiometer P_2 adjusts the circuit for firing at the proper zero point, while potentiometer P_3 controls the sensitivity of picking B, (in Fig. 3b); i.e., whether a line of given density will be recorded or not. The pulse coming from T, and corresponding to zero difference signal, is made to trip the thyratron, which in turn produces a spark which trips the illuminating arc. R_6 and the condenser of the thyratron, and R_7 and C_2 of the arc circuit, are set to have time constants of about 0.01 second.

Figure 3 shows the variations of voltage or current in various parts of the circuit as a line

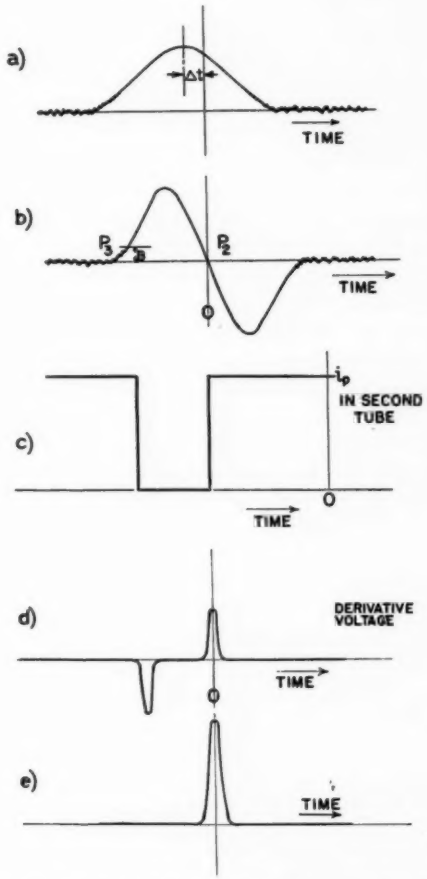

FIG. 3. Voltage variations in several parts of the circuit of Fig. 2 as a spectrum line passes across the scanning slit. (a) Variation in light intensity and multiplier output; (b) Signal obtained by combining inversely the attenuated multiplier output and the delay network output; (c) Variation in output of the "zero-picker" amplifier, designed to give a rapid voltage variation when the voltage in (b) falls to zero following a positive pulse; (d) Negative and positive pulses obtained from a transformer as a result of (c); (e) Positive pulse amplified for application to stroboscope lamp to give indication of passage of line maximum Δt second before.

passes across the microphotometer slit. Curve (a) shows the variation in multiplier output voltage, while (b) shows the difference between the delay-network input and output voltages. Curve (c) shows the plate current in the second tube of the "zero-picker" amplifier, while (d) represents the two pulses obtained from transformer T which result from its sudden changes in input current. Curve (e) shows the amplified positive pulse which is applied to the spark coil to fire the stroboscope arc which records the instantaneous reading of the rapidly rotating wave-length dial.

A time delay of 0.013 second corresponds to a distance along the plate of 0.052 mm when the plate is being scanned uniformly at 4 mm per second. At this speed a 20-inch spectrogram or transparent scale can be measured in 120 seconds, and the electrical system is found to respond satisfactorily provided no more than 4000 lines are recorded in this time. In the present case the limit is set by overheating of the arc. Slower speeds or higher resolution can be used if desired, as the delay network is arranged also to give delays of one-half and one-fourth the normal 0.013 second.

When the output voltage is delayed behind the input voltage by 13 milliseconds, it is necessary to compensate for half the delay by introducing a mechanical lag in the wave-length dial; this is done automatically and in the proper direction by means of a mechanical clutch which links the comparator drive to the wave-length drive. When the wave-length dial is being set for a particular plate the clutch is engaged to give direct drive; when the plate is being scanned the clutch is released and the wave-length drive shaft falls back a distance equal to that covered in half the delay time. When the plate is measured in the opposite direction, the wave-length shaft lags a similar amount in the opposite sense owing to the play in the collecting link. The looseness of coupling between comparator and wave-length shafts can be controlled by an adjustable collar which is calibrated on its edge in delay distances.

Ordinarily, each spectrum is measured once in each direction, and the readings taken in the two directions are averaged. In this way better values are obtained for broad, flat-topped lines, which may be "picked" slightly before their true center is reached, and residual asymmetries are somewhat compensated for. In general, errors in the machine are now much smaller than those inherent in the production of the lines themselves.

The automatic "maximum picker" described has been given careful tests for reproducibility in comparison with ordinary hand setting. Spectrum lines of various breadths were "picked" by the machine some twenty or thirty times in each direction. Then the same lines were set on by hand by an experienced operator. The average internal deviation of the sets of readings taken by hand operation was ± 0.002A, while that of those taken by machine was ± 0.0004A—a five-fold gain in precision. The "picker" operates most consistently on very narrow lines, but even on broad lines and on interferometer fringes it is usually superior to hand-and-eye setting. Hand setting seems superior to automatic setting only in the case of lines found on the broad wings of strong lines; again, in cases where no real maximum exists, the line may be omitted by the machine, whereas the eye sees it sharply by contrast. Eye settings are subject to psychological errors in such cases, however, and lines missed by the machine can usually be read from the density trace.

The increase in precision of setting by automatic means is particularly marked in the case of transparent scales ruled with sharp lines which are symmetrical. The reproducibility of setting may then become greater than the limit set by the resolution of the optical equipment used.

The precision attainable with the automatic "maximum picker" indicated the desirability of applying similar methods to increase the precision of hand-setting, which is still used in our laboratory for certain purposes. A scanning disk with a spiral slit was introduced between the projection lens of the comparator and its slit, and a cylindrical lens was placed in front of the latter. The disk was then rotated at such speed as to scan each spectrum line 20 times per second. The output of the electron multiplier was fed to a cathode-ray oscillograph placed in front of the operator. To remove possible shifts between line pattern and fiducial mark, this mark was produced by boring a small hole in the disk.

In setting on lines with this attachment, the comparator handle is moved until the peak of

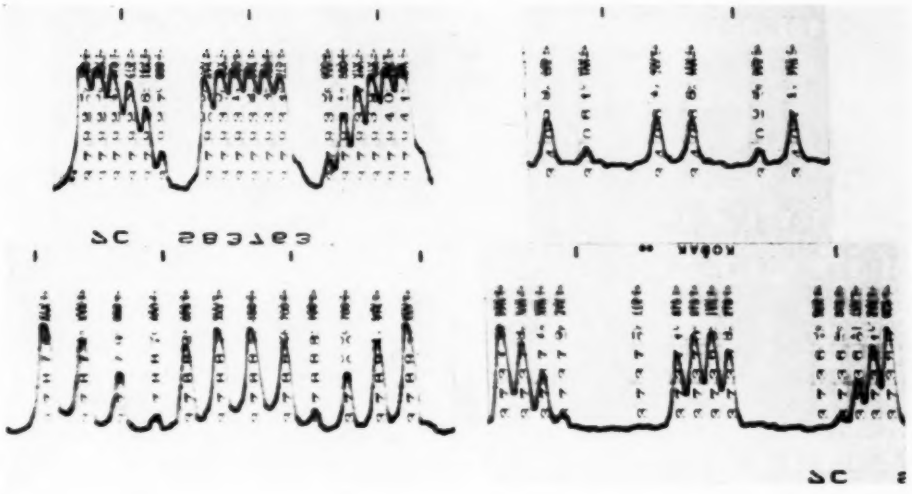

FIG. 4. Representative sections of wave-length and density records obtained when measuring Zeeman patterns with an automatic comparator using the new method of photometric balance for locating lines.

the spectrum line coincides with the peak of the narrower line produced by the hole. The principal advantage of the method is that the contour of a line is seen below the line itself; this gives much greater opportunity for estimating density changes and integrating density values by eye. In addition, the operator can control the sweep-circuit of the cathode tube so as to narrow or broaden the line pattern at will, so that broad or narrow lines can be set at the optimum width. The operator views each line on the oscillograph screen, presses a key when it is properly centered, and thus records photographically the wave-length which the dial indicates. This method has been found to increase at least 3-fold the reproducibility of line-setting by eye.

In Fig. 4 are shown several sections of records obtained with the automatic comparator in measuring Zeeman-effect spectrum plates. By adjusting potentiometer P_3 of Fig. 2, lines below any desired density can be omitted, so that minor irregularities in the background will not be recorded. The recorded dial readings give wave-lengths directly in angstroms to eight figures, though the last figure is usually ignored.

Two automatic comparators, each capable of measuring plates up to 24 inches in length, are now in operation. One of these instruments is being extended to record wave numbers as well as wave-lengths, and to reduce Fabry-Perot interferometer fringes automatically. Without this further development the cost of building an automatic comparator is estimated to be not more than $8000, including labor and materials.

We are grateful to Dr. V. K. Zworykin of the Radio Corporation of America, and to Mr. B. Ray Cummings of Farnsworth Radio and Television Corporation, for their cooperation in making suitable electron multipliers available for this work. We are also indebted to Mr. Horace Whittle of the Bell Telephone Laboratories for advice as to the practicability of constructing the delay network, and to Dr. Gerald Tawney for carrying out many of the details of calculation in connection with its design.

A Method for the Measurement of Flatness of Polished Surfaces*

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(Received May 25, 1940)

An optical method providing for the rapid inspection of extended surfaces is described. Two beams of parallel light are reflected by the sample through a cylindrical lens to form an astigmatic image of the source. If this image is a single line the surface is flat within the accuracy of the instrument. Radii of curvature in tested samples of the order of forty feet can be readily detected. An inspection device for testing glass to be used for photographic purposes is now in service.

OPTICAL flats or other instruments involving interference phenomena are customarily employed to measure the irregularity or curvature of surfaces of the type which may be generically described as "optically worked." Surfaces of a lower order of precision flatness or precision curvature may be measured by mechanical instruments such as feeler gauges, spherometers, or even straight-edge rulers.

The mechanical devices are slow and tedious to use if a complete point-by-point inspection of an extended surface is required. In many cases, moreover, there is some hazard of injury to the tested surfaces by the contacting areas of the instrument.

The instrument which is to be described here is an optical device which does not require mechanical contact. It is adapted to the rapid testing of extended surfaces and its range of sensitivity may, with some elaboration of design, be extended to the lower limit of the region ordinarily tested by interference methods.

A schematic diagram illustrative of the principle of the instrument is shown in Fig. 1. In this figure *A* is a concentrated source of light and *C* is a collimating lens. The lens *C* contains a mask *B* which is opaque except for two slits running in a direction normal to the paper. Light passing through the lens emerges as two parallel sheets of light of a thickness fixed by the slit openings and of a width equal to the length of the slits in lens *C*.

At *D* these two sheets of light encounter a strip circular cylindrical lens. If the light, after passing through this lens, were allowed to continue in the same direction, the two sheets would converge to form an astigmatic image of the source at a distance equal to the focal length of the cylinder. But if the light is reflected by a plane-polished surface at *E* back through the lens, the line image would be formed at a distance equal to half the focal length of the cylinder and this image might be viewed on a ground-glass screen placed at *F*.

If the mirror or other polished surface, instead of being plane, has a cylindrical curvature with an axis normal to the plane of the paper, the right- and left-hand sheets will encounter the reflecting surface at different angles; the cylindrical power of the system will be changed and the line image will be formed either above or below the plane *F*. In this event, on the screen

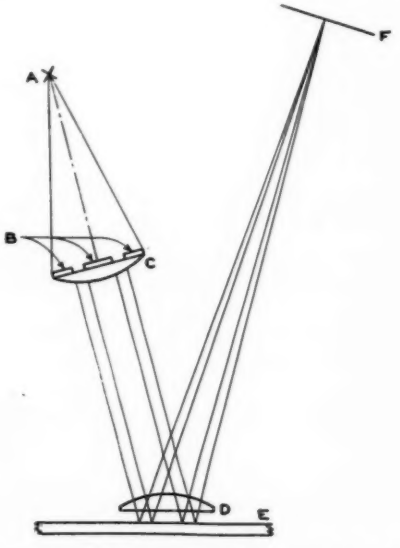

FIG. 1. Schematic diagram of optical system for flatness tester.

* Communication No. 768 from the Kodak Research Laboratories.

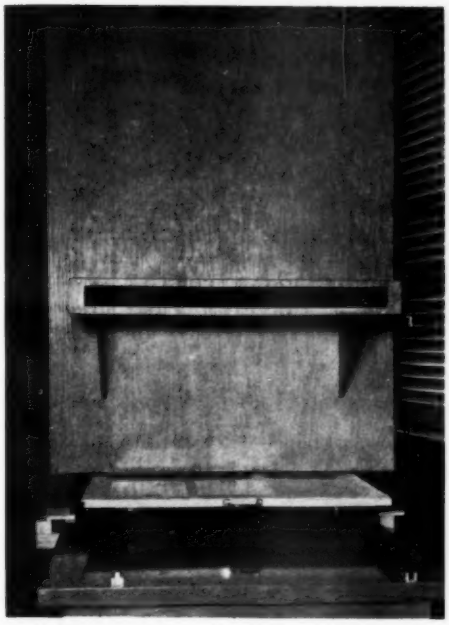

FIG. 2. Front view of glass tester.

fixed at *F* two lines will become visible. The separation of these lines will be a measure of the curvature of the surface being tested. Lines may be ruled on the ground glass, thus calibrating a scale to read the radius of curvature of the tested surface, the sagitta of the arc whose chord is the separation of the light beams, or the difference in the angle at which the two beams encounter the surface.

In some cases it is sufficient to know merely whether the surface is flat within the tolerances fixed by two lines on the glass screen. In others, it may also be required to know whether the curvature is convex or concave. This latter case necessitates that the observer of the ground-glass screen shall be able to distinguish between the right- and left-hand beams. One convenient method of distinguishing the beams is to cover the two slits in the lens with complementary color filters. If this is done, a plane surface will still produce a single white line, whereas a convex cylinder will result in, say, a blue-green line on top and a red line below, and a surface curvature of the opposite sign will reverse the position of the colored lines.

In the foregoing discussion only the top surface reflection has been considered, whereas in the case of glass and other transparent substances, reflection occurs at both surfaces. As long as the material is of uniform thickness so that its two surfaces are parallel, the double reflection introduces no new factor. If, however, the two surfaces are not parallel, each will produce its own line images on the screen. This phenomenon may be either useful or annoying, depending upon what imperfection the test is supposed to reveal.

In the testing of most transparent sheets, one is as interested in one surface as in the other. Two wavy surfaces may give rise to four line images. Should the separation of any pair of these images be beyond the predetermined flatness tolerances, the sample may have to be discarded, even though one surface might be good enough to pass the requirements. It is usually difficult with this testing method to differentiate between the two surfaces unless it is possible to immerse the sample partially in a liquid so as to destroy reflection from the lower surface. With some materials, however, enough light is absorbed by the double passage of the beams through the sample to bring about a distinguishable difference in the intensity of the first and second surface lens images.

One interesting application of the first and second surface reflection effect is in the measurement of a small amount of wedging and in determining the direction of this wedging. For example, let us take the case of a transparent material bounded by two plane surfaces inclined at an angle to each other. From each surface a single line image will be formed as a result of the coincidence of right- and left-hand beams. Images from the upper and lower surfaces will be separated by an amount which is dependent upon the degree of wedging. The appearance of the screen will resemble that resulting from a cylindrically curved sample, but if the complementary filters are used to distinguish between right- and left-hand sheets, the superposition of the two beams from each surface will give two white lines from the plane wedge and two colored lines from the cylinder, as was previously explained.

The sensitivity of an instrument operating on the principle illustrated in Fig. 1 is dependent

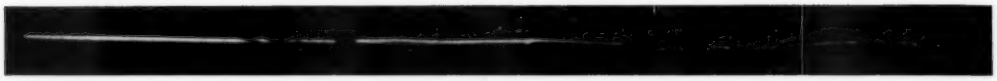

FIG. 3. Screen of tester showing traces of three different surfaces.

upon the geometry of the system, especially upon the optical lever arm which is the distance from the sample to the screen and upon the separation of the two beams. The first of these dimensions may be varied by a choice of the focal length of the cylindrical lens. The second is determined by the width of the cylindrical strip lens. Practical considerations limit the focal length to less than ten feet because the intensity of the image becomes undesirably low if the lever arm exceeds five feet. The beam separation should perhaps be limited to two inches on account of the cost of a strip cylinder of higher aperture.

The sensitivity of a flatness meter can be readily computed by means of the simple formula

$$\Delta = 16RS/D,$$

where Δ is the observed image separation, R is the length of the optical lever, S is the sagitta of the chord of length D, and D is the beam separation at the test surface. Thus, the sensitivity of a flatness meter having an optical lever arm of 5 feet and a beam separation of 2 inches, is one-half inch (image separation) per one-thousandth inch (0.001 inch) (the sagitta of the arc having a 2-inch chord). This is equivalent to a radius of curvature of 40 feet for the measured cylinder.

The size of the sample which can be inspected is limited by the width of the sheets of parallel light. This value is, of course, dependent upon the diameter of the spherical lens or more directly upon the length of the slits which can be contained within the circumference of this lens.

The problem of inspecting glass for photographic purposes and for gelatin filter coating was presented to these laboratories and a testing instrument capable of examining glass up to 30 inches wide was built following the schematic diagram of Fig. 1.

A collimating lens of sufficient diameter to permit the use of a mask with slits 30 inches long was obviously out of the question. There was, however, available a 40-inch focal length lens of 16-inch diameter. It was decided to build two inspection devices, each capable of examining a 15-inch width of glass, and to mount these side by side.

The large lens was sawed diametrically in two and from each half, adjacent to the diameter, a rectangular 2-inch by 15-inch lens segment was cut. These lenses were mounted, end to end, on a brass plate containing two $\frac{1}{2}$-inch slits, on $1\frac{1}{2}$-inch centers.

Each lens was illuminated by a 56-watt concentrated filament lamp placed at a distance of 40 inches above the lenses and a mask between the sources was installed to prevent light from each lamp from reaching the wrong lens. Two strip cylindrical lenses of 80-inch focal length, 2 inches wide, and 15 inches long, were mounted to receive the beams from the collimating lenses. Beneath these lenses a space for inserting the test materials was provided. The front surface mirror 30 inches long was installed to reflect the converging sheets of light outward in a horizontal direction to a conveniently located opal-glass screen.

A front view of this apparatus is shown in the photograph (Fig. 2). On the screen are visible the images from three samples of glass laid side by side beneath the cylindrical lens. At the left is a sample of very good polished plate which is neither wedged nor curved. The center sample is a piece of window glass which is flat along one edge and curved along the other. The sample at the right is a piece of poorer window glass containing ripples on both surfaces. An enlarged view of the screen showing these patterns more clearly is shown in Fig. 3.

The whole device is mounted on a table. The sample carrier is a plush-covered flat board mounted on roller-bearing wheels running on a track so that it can be pushed under the optical system. One operator works at the screen end putting on glass samples and a second workman removes the glass at the far end. It is possible to inspect about 500 sheets per hour, each sheet being run through first in one direction and then rotated 90 degrees and run through again.

Fabry-Perot Interferometers in a Parallel Arrangement

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The intensity equation of two Fabry-Perot interferometers operated in parallel is obtained and discussed. It is observed that the distribution complementary to that of a single Fabry-Perot instrument has very significant properties and may be obtained by such an arrangement.

INTRODUCTION

THE properties of interference patterns produced by two Fabry-Perot interferometers in a series arrangement have been more or less completely investigated, both theoretically and experimentally, by Perot and Fabry,[1] Houston,[2] Gehrcke and Lau,[3] and others. However, the properties and possibilities of two Fabry-Perot interferometers placed in a parallel arrangement appear not to have been studied. Superficial examination of such an arrangement leads one to anticipate that it might be more suitable for many purposes than the interferometers in series.

The idea of placing two Fabry-Perot interferometers in parallel was suggested by a study of the general intensity equation derived in a former paper[4] in an attempt to discover the conditions for obtaining the intensity distribution pattern complementary to that transmitted through a single Fabry-Perot interferometer.[5] The distribution for the Fabry-Perot interferometer is described by the equation:

$$I_f = \frac{I_{\max}}{1+F\sin^2(\alpha/2)}, \qquad (1)$$

where $F=4r/(1-r)^2$, called the *coefficient de finesse* by Fabry. For convenience, (1) will be referred to as the "finesse" distribution. The complementary distribution, which may be called "cofinesse," is:

$$I_c = I_{\max}\frac{F\sin^2(\alpha/2)}{1+F\sin^2(\alpha/2)}. \qquad (2)$$

This distribution is significant, for not only does it have zero minima, no secondary maxima, and high visibility, but it has a higher spectral resolution than the finesse distribution.

A study of the generic properties of the general interference equation[4] leads immediately to the conclusion that zero minima occur only when equal beams are superposed, and that secondary maxima disappear only when two beams or an infinite number of beams are superposed. Therefore, it was observed that the general interference equation reduces to the cofinesse distribution when two infinite sets of beams (as produced by a Fabry-Perot interferometer) having corresponding beams of equal amplitudes and the initial beams of the two sets opposite in phase are superposed. It was then observed that these conditions might be fulfilled by placing two Fabry-Perot interferometers in a parallel arrangement. Such an arrangement will be discussed in this paper.

DERIVATION OF INTENSITY EQUATION

Two Fabry-Perot interferometers may be operated in parallel by placing a pair of variable separation surfaces in each arm of a Mach interferometer. Such an arrangement is illustrated in

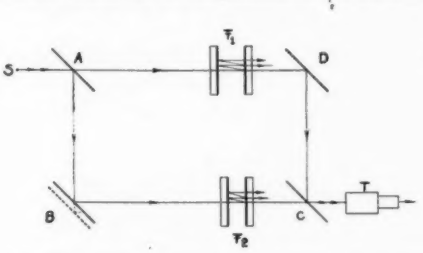


FIG. 1. Two Fabry-Perot interferometers in a parallel arrangement. Parallel monochromatic light from a source S passes through the instrument and is viewed by a telescope T.

[1] Perot and Fabry, Ann. Chim. Phys. [7], **16**, 289 (1899).
[2] W. V. Houston, Phys. Rev. **29**, 478–484 (1927).
[3] E. Gehrcke and E. Lau, Physik. Zeits. **31**, 973 (1930).
[4] L. Sturkey and B. P. Ramsay, "A general interferential method." This paper will shortly appear in Phil. Mag.
[5] W. E. Anderson, J. Opt. Soc. Am. **27**, 300–302 (1937).

Fig. 1. In this diagram, A and C are half-silvered plates and B and D are full-silvered. F_1 and F_2 are Fabry-Perot instruments with identically silvered plates, the plates in one being parallel to those in the other.

The beams superposed at the telescope T may be divided into two sets:

First set—Z_1

$$\text{amplitudes} = s,\ sr,\ sr^2,\ sr^3 \cdots sr^{k-1},$$
$$\text{phases} = 0,\ \alpha_1,\ 2\alpha_1,\ 3\alpha_1 \cdots (k-1)\alpha_1.$$

Second set—Z_2

$$\text{amplitudes} = s,\ sr,\ sr^2,\ sr^3 \cdots sr^{k-1},$$
$$\text{phases} = \phi,\ \phi+\alpha_2,\ \phi+2\alpha_2,\ \phi+3\alpha_2, \cdots \phi+(k-1)\alpha_2,$$

where

ϕ is the phase difference introduced by any difference in the optical paths for light through ABC and ADC;

α_1 is the phase difference introduced by one reflection between the plates F_1;

α_2 is the phase difference introduced by one reflection between the plates F_2; and

r is the square of the amplitude reflection coefficient of the plates.

The intensity distribution resulting from the superposition of two such series of beams may be found by applying a general "method of interference."[4] For, if two such sets of the above type are superposed:

$$I = Z_1^2 + Z_2^2 + 2Z_1Z_2 \cos\left[\phi + (\beta_2 - \beta_1)\right], \quad (3a)$$

where

$$Z_1^2 = s^2 \frac{(1-r^k)^2 + 4r^k \sin^2 (k\alpha_1/2)}{(1-r)^2 + 4r \sin^2 (\alpha_1/2)}, \quad (3b)$$

$$\cos \beta_1 = \frac{s}{Z_1} \frac{r^{k+1} \cos (k-1)\alpha_1 - r^k \cos k\alpha_1 - r \cos \alpha_1 + 1}{(1-r)^2 + 4r \sin^2 (\alpha_1/2)}, \quad (3c)$$

$$\sin \beta_1 = \frac{s}{Z_1} \frac{r^{k+1} \sin (k-1)\alpha_1 - r^k \sin k\alpha_1 + r \sin \alpha_1}{(1-r)^2 + 4r \sin^2 (\alpha_1/2)} \quad (3d)$$

and similar expressions for Z_2^2, $\sin \beta_2$, and $\cos \beta_2$. The resulting intensity distribution then becomes:

$$I = 2s^2 \frac{(1+\cos \phi) + r^2[1+\cos (\phi+\alpha_1-\alpha_2)] - r[\cos \alpha_1 + \cos (\phi-\alpha_1) + \cos \alpha_2 + \cos (\phi-\alpha_2)]}{(1+r^2-2r \cos \alpha_1)(1+r^2-2r \cos \alpha_2)}. \quad (4)$$

Cases of this equation will be discussed.

Discussion

Case I. $\phi = 0$

If the phase difference between the initial beams in the two sets is zero, the intensity Eq. (4) assumes the form:

$$I_0 = s^2 \frac{4 + 2r^2[1+\cos (\alpha_2-\alpha_1)] - 4r[\cos \alpha_1 + \cos \alpha_2]}{(1+r^2-2r \cos \alpha_1)(1+r^2-2r \cos \alpha_2)}. \quad (5)$$

Besides being complex, and consequently difficult of interpretation, this distribution does not have zero minima. However, one instance in which such a distribution may be significant or useful occurs when $\alpha_1 = \alpha_2 = \alpha$. Then I_0 reduces to the finesse distribution:

$$I_0' = s^2 \frac{4}{1+r^2-2r \cos \alpha}. \quad (6)$$

It is probable that the distribution (5) will not be useful for practical purposes; for it appears that whenever the separation of the two pairs of plates are such that some maxima due to the terms in

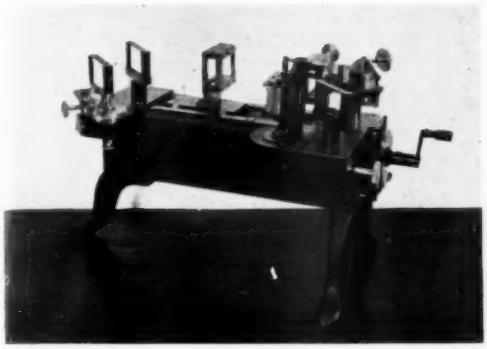


FIG. 2. An interferometer consisting of two Fabry-Perot instruments in a parallel arrangement, one pair of Fabry-Perot plates being mounted in contact.

the denominator coincide, minima of the numerator occur. The numerator then has the effect of smearing out the maxima caused by the denominator terms.

Case II. $\phi=\pi$

If a phase difference of π is introduced between the initial beams of the two sets, the intensity distribution becomes:

$$I_\pi = s^2 \frac{4r^2 \sin^2 (\alpha_2-\alpha_1)/2}{(1+r^2-2r\cos\alpha_1)(1+r^2-2r\cos\alpha_2)}. \quad (7)$$

This distribution becomes significant in two instances:

(a) If $\alpha_2=2\alpha_1=2\alpha$, Eq. (7) becomes:

$$I_\pi' = s^2 \frac{4r^2 \sin^2 \alpha/2}{(1+r^2-2r\cos\alpha)(1+r^2-2r\cos 2\alpha)}. \quad (8)$$

This is evidently the product of a cofinesse distribution and a finesse distribution of twice the "frequency." This intensity pattern has zero minima and sharp, intense maxima. Consequently, it has a higher visibility and resolving power than that of a Fabry-Perot interferometer. However, the secondary maxima, though of relatively low intensity, may be troublesome.

In general then, (7) becomes such a significant distribution when the separation of one pair of Fabry-Perot plates is an even multiple of the separation of the other pair; i.e., $\alpha_2=2n\alpha_1$.

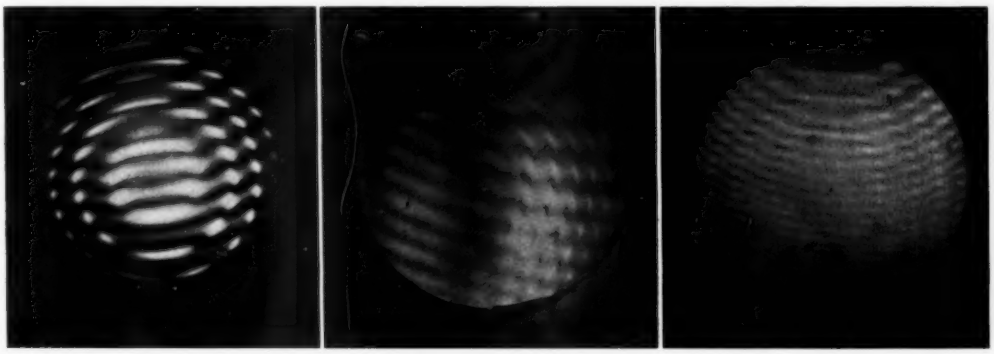
(b) If $\alpha_2=0$, (7) reduces to the cofinesse intensity distribution:

$$I_\pi'' = s^2 \frac{4r^2}{(1-r)^2} \frac{\sin^2 \alpha/2}{(1-r)^2+4r\sin^2 \alpha/2}. \quad (9)$$

That is, the cofinesse intensity pattern appears when the plates of one pair are in contact, or their separation is very small compared to that of the other pair. It may also be observed that for this case, provided there is no intensity loss due to absorption, the silver may be removed from the surfaces of the plates in contact.

EXPERIMENTAL OBSERVATIONS

An interferometer was constructed which consisted essentially of two Fabry-Perot interferometers placed in the arms of a Mach interfer-



(a) (b) (c)

FIG. 3. Fringe patterns formed by the interferometer of Plate I. (In (c) above, the silver has been removed from the surfaces of the contact plates.)

ometer. However, since the cofinesse distribution appears to be the most significant distribution obtainable from such a parallel arrangement, provision was made for mounting one pair of plates in contact. A photograph of the instrument appears in Fig. 2. These contact plates could be rotated as a unit about both horizontal and vertical axes. The mirror B (Fig. 1) could be rotated about a vertical axis and could be moved perpendicular to itself to change the path difference of the two initial beams. The mirror D could be rotated about a horizontal axis.

Photographs obtained with the instrument using the green line of mercury appear in Fig. 3. The photograph lettered (c) was taken with the silver removed from the surfaces of the contact plates. It may be seen that within the bands where $\phi=\pi$ the intensity distribution is cofinesse.

In order to use these fringes for actual measurements on spectral lines with the aid of a microphotometer, the bands where $\phi=\pi$ must be straight, and one must cross the center of the finesse circles. To obtain truly straight bands, both pairs of plates should be initially placed in contact, and white-light fringes obtained by adjusting the instrument as a Mach interferometer.

Conclusion

This discussion of the parallel arrangement of Fabry-Perot interferometers may lead to the development of procedures for its application to spectroscopic purposes. In addition to this, it will be helpful in illustrating certain general rules for the use of optical devices in parallel and series arrangements. These rules are being studied in the laboratory where this work was done.

Acknowledgment

The author wishes to acknowledge his indebtedness to Dr. B. P. Ramsay of the University of Kentucky for his assistance in the preparation of this material.

The Optical Properties of the Grating Interferometer

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(Received June 2, 1940)

Observations made with the grating interferometer suggest that it may be useful for the study of fine structure. It is hoped that the peculiarities of the instrument and a satisfactory procedure for its application to a study of fine structure of spectral lines can be described in a later paper. At present certain optical properties of the instrument are catalogued. The optical properties are themselves interesting and will be found useful in discussing applications which may be described subsequently.

INTRODUCTION

A GRATING interferometer is an instrument which is produced by substituting gratings for the mirrors in the arms of the usual form of the Michelson interferometer. The construction, adjustment and action of such an instrument has been described.[1] The optical properties and possibilities of instruments of this type have not as yet been carefully examined. Expressions for these optical properties may be obtained directly or they may be derived from the general intensity function which is applicable to the instrument. The latter procedure is somewhat more satisfactory and will be followed here. The intensity equation has been given[1] as

$$I=A_1^2+A_2^2+2A_1A_2\cos\gamma, \tag{1}$$

where

$$A_1=(a_1c_1)\frac{\sin\pi a_1\theta_1}{\pi a_1\theta_1}\frac{\sin\pi\sigma_1\theta_1N_1}{\sin\pi\sigma_1\theta_1}. \tag{2}$$

A_2 may be expressed similarly and γ is the phase difference between the two beams.

Although the value of γ in Eq. (1) is not specified, it may be obtained from the geometry of the optical paths. A form of the intensity equation in which the value of γ explicitly appears has been derived by L. Sturkey and B. P. Ramsay.[2] This equation is

$$I=\rho_1\left(\frac{\sin k\alpha/2}{\sin\alpha/2}\right)^2+\rho_2\left(\frac{\sin n\beta/2}{\sin\beta/2}\right)^2+2\rho_1\rho_2\left(\frac{\sin k\alpha/2\sin n\beta/2}{\sin\alpha/2\sin\beta/2}\right)\times\cos\left[\phi+\frac{(n-1)\beta-(k-1)\alpha}{2}\right]. \tag{3}$$

It is obvious that Eqs. (1) and (3) are identical provided

$$\gamma=\phi+\frac{(k-1)\alpha-(n-1)\beta}{2}, \tag{a}$$

$$k=N_1+1, \tag{b}$$

$$n=N_2+1, \tag{c}$$

$$\alpha=\pi\sigma_1\theta_1/\lambda=\pi\sigma_1(\sin i_1+\sin i_1')/\lambda, \tag{4}$$

$$=\frac{2\pi\sigma_1}{\lambda}\sin i_1 \text{ at minimum deviation,} \tag{d}$$

$$\beta=\frac{2\pi\sigma_2}{\lambda}\sin i_2 \text{ at minimum deviation,} \tag{e}$$

$$\rho_1=(a_1c_1)\frac{\sin\pi a_1\theta_1}{\pi\alpha_1\theta_1} \tag{f}$$

and a similar expression for ρ_2.

Three different adjustments of the grating interferometer are to be considered.

I. If the gratings are set for normal incidence both θ_1 and θ_2 are equal to zero; the intensity equation then becomes

$$I=(a_1c_1)^2+(a_2c_2)^2+2(a_1c_1)(a_2c_2)\cos\phi. \tag{5}$$

This is the usual form for the intensity equation

[1] B. P. Ramsay, J. Opt. Soc. Am. **24**, 253–258 (1934); Zeits. f. Instrumentenk. **55**, 134 (1935).

[2] L. Sturkey and B. P. Ramsay, "A general interferential method." This paper will shortly appear in Phil. Mag.

of a two-beam interference, such as is effected by the Michelson mirror interferometer. This setting may be called the Michelson adjustment of the grating interferometer.

II. If the gratings are rotated in the same direction to positions of minimum deviation for some wave-length λ, the amplitude factors in Eq. (3) will not depend upon the direction of rotation of the gratings; but the value of γ will. It becomes

$$\gamma = \pm\phi' \pm \frac{(n-1)\beta' + (k-1)\alpha'}{2}, \qquad (6)$$

where α' and β' are the absolute values of α and β, respectively. This is the arrangement of the optical parts which is called the chromatic adjustment. Eq. (6) shows that there are two subdivisions to be made of this case. They may be called (A) the additive setting of the chromatic adjustment, and (B) the subtractive setting of the chromatic adjustment. By (A) it is meant that the sign of ϕ' is the same as that of the other term on the right side of Eq. (6), whereas, by (B) it is meant that the sign of ϕ' is different from that of the other term. It can be anticipated that there are also physical reasons for distinguishing between the additive and subtractive settings.

III. If the gratings are rotated in the opposite directions to positions of minimum deviation, the value of γ is

$$\gamma = \pm\phi' \pm \frac{(n-1)\beta' - (k-1)\alpha'}{2}. \qquad (7)$$

This is the arrangement of the optical parts which is called the complementary adjustment. In this case also the additive and subtractive settings must be considered separately.

It was shown in the previous discussion[1] of the grating interferometer that when the gratings are adjusted for minimum deviation of some particular wave-length λ, the gratings are approximately, but not exactly, in the position of minimum deviation of some wave-length $\lambda' = \lambda + \Delta\lambda$. This follows because the dispersion of the gratings[3]

$$\frac{di}{d\lambda} = \frac{m}{\sigma \cos i} \qquad (8)$$

is practically constant for a limited region of wave-lengths.

It is also possible to see what will happen by examining the formula for maxima

$$\sin i = m(\lambda + \Delta\lambda)/\sigma - \sin i'. \qquad (9)$$

When the gratings are illuminated with parallel light, $\sin i$ is constant for all values of $\lambda + \Delta\lambda$; consequently, the angle of diffraction for $\lambda + \Delta\lambda$ will be greater than the angle of minimum deviation for λ. When the gratings are adjusted for minimum deviation of λ, the two beams of wave-length λ from the two arms of the interferometer are superimposed. Furthermore, in the complementary setting the beams of wave-length $\lambda' = \lambda + \Delta\lambda$ are also superimposed if the distances of the gratings from the half-silvered mirrors are equal; but, in the chromatic orders the slit images of λ' will lie on both sides of the superimposed images of wave-length λ.

There are, therefore, real physical differences between the optical phenomena produced by the chromatic and complementary adjustments. For example, consider the situations which arise when the two gratings used in the arms of the interferometer are identical. For the chromatic orders the intensity function, Eq. (3), becomes

$$I = 4\rho^2 \left[\frac{\sin k\alpha/2}{\sin \alpha/2}\right]^2 \cos^2 \left[\pm\frac{\phi}{2} \pm \frac{\beta - \alpha}{2}\right], \qquad (10)$$

for complementary orders however

$$I = 4\rho^2 \left[\frac{\sin k\alpha/2}{\sin \alpha/2}\right]^2 \cos^2 \frac{\phi}{2} \qquad (11)$$

and under the same condition the intensity function, Eq. (5) for the Michelson adjustment becomes

$$I = 4(ac)^2 \cos^2 \phi/2. \qquad (12)$$

Since the order of interference, dispersion, and resolving power of the interferometer depend upon the value of γ only, comparison of Eqs. (11) and (12) reveals that the optical properties are the same in the Michelson and complementary setting for an instrument using identical gratings adjusted for the same order. The unique properties and possibilities of the grating interferometer are therefore to be found in the chromatic adjustment.

[3] L. W. Taylor, *College Manual of Optics* (Ginn and Company, 1924), p. 59.

II. Order of Interference and Resolving Power

From the intensity equation, Eq. (1), it may be seen that the maximum value of the intensity occurs where $\cos\gamma=1$, or

$$\gamma=2\pi n_0. \tag{13}$$

In this equation n_0 is called the order of interference. The phase difference, γ, is related to the optical path difference, D, by the formula

$$\gamma/2\pi=D/\lambda, \tag{14}$$

thus

$$n_0=\frac{\gamma}{2\pi}=\frac{D}{\lambda}=\frac{2\mu T\cos\theta}{\lambda}, \tag{15}$$

where T is the total effective path difference in length of the interferometer arms, and θ is the angle between the normal connecting the two parallel wave fronts and the line joining the position of a maximum of the fringe system with the foot of this perpendicular.[4] The analogy between the action of gratings and reflections for mirrors may be extended by calling θ the angle between the transmitted and reversed beams which correspond to one particular ring of the interference pattern whose order is n_0. In the notations employed for gratings $\theta=\Delta i=\Delta i'$ for any ray of wave-length λ not exactly incident at the angle of minimum deviation $i=i'$.

The order of interference is simply defined as the path difference measured in wave-lengths.[5] Thus for the Michelson adjustment the optical path difference introduced by a difference, t, in the length of the interferometer arms is

$$d/\lambda=\mu t\cos\theta/\lambda. \tag{16}$$

This corresponds to a phase difference γ_0 which is given by

$$\gamma_0/2\pi=\mu t\cos\theta/\lambda \tag{17}$$

or

$$\gamma_0=(2\pi/\lambda)\mu t\cos\theta. \tag{18}$$

Since the wave is reflected back over the same optical path, the total phase difference is

$$\phi=2\gamma_0=(2\pi/\lambda)2\mu t\cos\theta. \tag{19}$$

Thus ϕ in Eq. (3) and elsewhere is half of the phase difference which arises because of the positions of the gratings in the interferometer arms; it does not depend upon their orientation. Comparison of Eqs. (6) and (7) shows that the order of interference in the complementary and chromatic orders depends on both the separation of the interferometer arms and on the orientation of the gratings.

The contribution of both gratings can be additive to the contribution of the difference in position of the gratings in the interferometer arms in the case of the chromatic adjustment. This is shown by comparison of Eqs. (6) and (7). The maximum order of interference is obtainable in the additive setting of the chromatic adjustment.

The spectroscopic resolving power, R, of any optical instrument is the maximum order of interference which it will produce.[5] Thus the resolving power of the grating interferometer adjusted for the additive setting is given by Eq. (6) as

$$R=\frac{D_{\max}}{\lambda}=\frac{\gamma_{\max}}{2\pi}$$

$$=\frac{1}{2\pi}\left[\phi'+\frac{(k-1)\alpha'+(n-1)\beta'}{2}\right]. \tag{20}$$

From Eq. (19)

$$\phi'=2\gamma_0=\left[\frac{4\pi\mu t}{\lambda}\cos\theta\right]_{\max}=\frac{4\pi\mu t}{\lambda}. \tag{21}$$

Likewise from Eq. (4)

$$(k-1)\alpha'=2\gamma_1=\frac{2\pi}{\lambda}[2N_1\sigma_1(\sin i_1+\sin i_1')], \tag{22}$$

which, by the formula for maxima, may be written as

$$(k-1)\alpha'=4\pi N_1\sigma_1(m_1/\sigma_1)=4\pi m_1N_1. \tag{23}$$

Similarly

$$(n-1)\beta'=2\gamma_2=4\pi m_2N_2. \tag{24}$$

Substitution of the values given in Eqs. (21), (23) and (24) into Eq. (20) yields

$$R=2\mu t/\lambda+m_1N_1+m_2N_2. \tag{25}$$

[4] W. E. Williams, *Applications of Interferometry* (Dutton, 1930), p. 47.
[5] W. E. Williams, reference 4, p. 27.

If the gratings used are identical (e.g., good replicas of the same grating) and if the gratings are adjusted for the same order, $m_1=m_2=m$ and $N_1=N_2=N$; the expression for the resolving power becomes

$$R=2\mu t/\lambda+2mN. \tag{26}$$

For the complementary adjustment the resolving power is found by substitution of Eqs. (21), (23) and (24) into

$$R=\frac{1}{2\pi}\left[\phi'+\frac{(k-1)\alpha'-(n-1)\beta'}{2}\right]. \tag{27}$$

For identical gratings adjusted for the same order of diffraction the result is

$$R=2\mu t/\lambda. \tag{28}$$

This is the same as for the Michelson adjustment.

The resolving power in the chromatic adjustment thus increases with the number of rulings on the gratings and with the order of diffraction. Substitution of probable values ($t=2$ centimeters, $m=1$, $N=47{,}000$) into Eq. (26) shows that the theoretical resolving power of the instrument is of the order of 1.6×10^5. The resolving power might be further increased by the substitution of reflection echelons for the gratings in the interferometer arms. Michelson has succeeded in constructing transmission echelons with a resolving power as high as 9×10^5. When reflection echelons are used, the resolving power is three to four times as large.[6] The substitution would give a theoretical resolving power of approximately 75×10^5. Williams has employed the fringes formed by placing a reflection echelon in one of the arms of a Twyman-Green interferometer as a test of the echelons.[7]

Equation (25) for the resolving power gives merely the maximum value of the order of interference obtainable with the grating interferometer. The general expression for the order of interference is Eq. (15) where

$$T=\pm t\pm\frac{m_1N_1\lambda+m_2N_2\lambda}{2}. \tag{29}$$

Thus

$$n_0=\frac{2\mu}{\lambda}\left[\pm t\pm\frac{m_1N_1\lambda+m_2N_2\lambda}{2}\right]\cos\theta. \tag{30}$$

In this relation t may be considered a directed quantity which determines the sign of the first term. The physical conditions which determine its sign are obvious; for, conventions which have already been adopted[8] determine the sign of the last two terms on the right side of Eq. (29). Thus, the quantities N_1 and N_2 are essentially positive; but the signs of the orders of diffraction (m_1 and m_2) are taken as positive when the gratings are rotated in a counter-clockwise direction and negative when rotated in a contrary sense. Therefore, no more can be said concerning the sign of the first term than that it may be determined from the geometry of the interferometer. It must have the same sign as the resultant of the last two terms if t has such a direction as to increase the path difference introduced by the orientations of the gratings; otherwise, it has the opposite sign.

It is possible to list as formulas the values of n_0 for the various adjustments of the interferometer listed in the introductory paragraphs.

I. For the Michelson adjustment (for which $m_1=m_2=m$)

$$n_0=\pm\frac{2\mu t}{\lambda}\cos\theta. \tag{31}$$

II. For the chromatic adjustment (m_1 and m_2 are both positive or both negative)

(A) in the additive setting

$$n_0=\frac{2\mu}{\lambda}\left[\pm t\pm\frac{(m_1N_1+m_2N_2)\lambda}{2}\right]\cos\theta. \tag{32}$$

(B) in the subtractive setting

$$n_0=\frac{2\mu}{\lambda}\left[\mp t\pm\frac{(m_1N_1+m_2N_2)\lambda}{2}\right]\cos\theta. \tag{33}$$

III. For the complementary adjustment (m_1 and m_2 are unlike in sign)

[6] W. E. Williams, reference 4, p. 28.
[7] W. E. Williams, Proc. Phys. Soc. **45**, 699 (1933).
[8] B. P. Ramsay, J. Opt. Soc. Am. **24**, 253–258 (1934).

(A) in the additive setting

$$n_0=\frac{2\mu}{\lambda}\left[\pm t\pm\frac{(m_1N_1-m_2N_2)\lambda}{2}\right]\cos\theta. \quad (34)$$

(B) in the subtractive setting

$$n_0=\frac{2\mu}{\lambda}\left[\mp t\pm\frac{(m_1N_1-m_2N_2)\lambda}{2}\right]\cos\theta. \quad (35)$$

III. Magnifying Power

For many purposes for which the Michelson interferometer is useful, the circular fringes at infinity must be employed. The use of these fringes is attended by the difficulty that their linear width becomes smaller as the path difference is increased. For high orders of interference, the fringes eventually become too fine to be used. This decrease in width is not an unavoidable consequence of the order of interference; but, it results from the necessary point-to-point correspondence of the interfering wave fronts and the fact that the simple Michelson instrument depends solely upon the separation of these wave-fronts to effect high orders. The grating interferometer effects high orders not only through this means but also through the constant terms m_1N_1 and m_2N_2 which appear in Eq. (25) for the resolving power. Thus, the wave front producing an order of interference of 200,000 in the grating interferometer may have a separation no greater than that of the wave fronts producing the order of interference 2000 in the Michelson interferometer. The fringe of order 200,000 in the grating device is therefore magnified to have the dimensions of the fringe of order 2000 as produced by the unmodified Michelson interferometer.

An expression for this magnification can be found in the following manner. The angular diameter of a circular fringe in the Michelson interferometer is given[9] as

$$\delta_n=(n_0\lambda/t)^{\frac{1}{2}}, \quad (36)$$

where n_0 is the order of interference; and t is the separation of the mirrors. The angular width of any circular fringe is half the difference of the angular diameters of adjacent circles. Thus, it is

$$W_1=\frac{\delta_n-\delta_{(n+1)}}{2}=\frac{1}{2}\left\{\left(\frac{n_0\lambda}{t_1}\right)^{\frac{1}{2}}-\left(\frac{(n_0+1)\lambda}{t_1}\right)^{\frac{1}{2}}\right\}. \quad (37)$$

Since $n_0\rangle\rangle\rangle 1$, this reduces to

$$W_1=\tfrac{1}{2}(\lambda/t_1)^{\frac{1}{2}}. \quad (38)$$

The ratio of the angular width of any two circular fringes is

$$W_1/W_2=(t_2/t_1)^{\frac{1}{2}}. \quad (39)$$

This expression can be used as a measure of the magnification effected by the grating interferometer if the symbols are accorded the following significance; W_1 is the angular width of a circular fringe of order n_0 produced by a grating interferometer for which the actual separation of the arms is t_1; and W_2 is the width of the fringe of the same order as produced by the Michelson mirror interferometer having the mirror separation t_2. Since the resolving power of these two instruments is the same when using interference of the same order, a relation between t_1 and t_2 may be obtained, that is

$$2\mu t_2/\lambda=2\mu t_1/\lambda+2mN. \quad (40)$$

From this equation it may be seen that

$$\frac{W_1}{W_2}=\left(1+\frac{mN\lambda}{\mu t_1}\right)^{\frac{1}{2}}. \quad (41)$$

The magnifying power, P, of a grating interferometer may be defined as the value of the magnification produced when $\mu=1$ and $t_1=1$. From Eq. (41) this is seen to be

$$P=(1+mN\lambda)^{\frac{1}{2}}. \quad (42)$$

For an interferometer fitted with echelons as suggested above, the magnifying power is approximately seven. From Eq. (42) it may be seen that the magnifying power is a parabolic function of the parameters m, N, or λ; the other two being considered constant.

In deriving Eq. (42) it has been assumed that the angular width of the fringes depends upon the length of the interferometer arms only and not at all upon the order of interference. With the grating interferometer, it is possible to change the order of interference without changing the lengths of the interferometer arms (e.g., in posi-

[9] W. L. Taylor, reference 3, p. 115.

tions of chromatic orders). The validity of the assumption made, however, needs experimental proof.

To show that the adjustment for chromatic orders (as well as for the Michelson and complementary orders) does not alter the angular width of the fringes, it is necessary to compare the angular width of two fringes in the chromatic and Michelson (or the complementary) orders which have the same diameters. Two such fringes, having the same diameter but different orders, will also have the same angular widths if the assumption made above is correct. Not only is this true but also every other pair of fringes in the fields of view with the same difference in length of the interferometer arm will have the same angular widths. Careful measurements made of photographs of the fringes show that these conclusions are valid.

Dispersion

The angular dispersion of the instrument is the rate of change in position of the fringe of order n_0 with wave-length. That is, the dispersion is

$$D=(d\theta/d\lambda),\ n_0=\text{constant}. \tag{43}$$

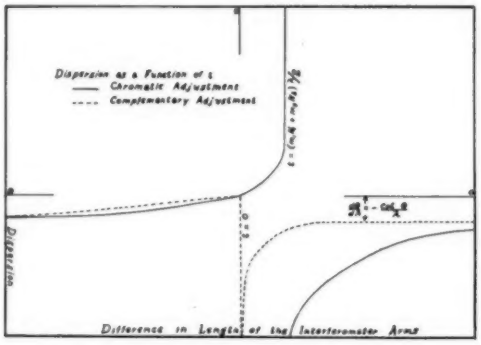

Fig. 1.

It can be obtained by differentiating Eq. (15)

$$n_0\lambda=2\mu T\cos\theta, \tag{44}$$

$$\frac{n_0}{2\mu}=-T\sin\theta\frac{d\theta}{d\lambda}+\cos\theta\frac{dT}{d\lambda}, \tag{45}$$

$$\frac{d\theta}{d\lambda}=-\frac{n_0}{2\mu T\sin\theta}+\frac{\cot\theta}{T}\frac{dT}{d\lambda}. \tag{46}$$

The derivative in the second term on the right of Eq. (46) is a novelty introduced by the peculiarities of the instrument. Its effect on the dispersion can best be seen by considering the several cases noted above separately. The general expression for T is

$$T=\pm t\pm(m_1N_1\lambda\pm m_2N_2\lambda)/2. \tag{47}$$

I. For the Michelson adjustment

$$T=t, \tag{48}$$

$$dT/d\lambda=dt/d\lambda=0 \tag{49}$$

and

$$n_0=2\mu t\cos\theta/\lambda. \tag{50}$$

Hence the dispersion is given by

$$d\theta/d\lambda=-\cot\theta/\lambda. \tag{51}$$

II. For the chromatic adjustment
(A) in the additive setting

$$T=\pm t\pm(m_1N_1+m_2N_2)\lambda/2, \tag{52}$$

$$dT/d\lambda=\pm(m_1N_1+m_2N_2)/2. \tag{53}$$

Substitution of Eqs. (44) and (53) into (46) gives the following expression

$$\frac{d\theta}{d\lambda}=-\frac{\cot\theta}{\lambda}+\frac{(m_1N_1+m_2N_2)\cot\theta}{2[t+(m_1N_1+m_2N_2)\lambda/2]}. \tag{54}$$

(B) In the subtractive setting

$$T=\mp t\pm(m_1N_1+m_2N_2)\lambda/2, \tag{55}$$

$$dT/d\lambda=\pm(m_1N_1+m_2N_2)/2. \tag{56}$$

Substitution of Eqs. (44) and (56) into (46) yields

$$\frac{d\theta}{d\lambda}=-\frac{\cot\theta}{\lambda}-\frac{(m_1N_1+m_2N_2)\cot\theta}{2[t-(m_1N_1+m_2N_2)\lambda/2]}. \tag{57}$$

III. For the complementary adjustment
(A) in the additive setting

$$T=\pm t\pm(m_1N_1-m_2N_2)\lambda/2, \tag{58}$$

$$dT/d\lambda=\pm(m_1N_1-m_2N_2)/2. \tag{59}$$

Substitution of Eqs. (44) and (59) into (46) yields

$$\frac{d\theta}{d\lambda}=-\frac{\cot\theta}{\lambda}+\frac{(m_1N_1-m_2N_2)\cot\theta}{2[t+(m_1N_1-m_2N_2)\lambda/2]}. \tag{60}$$

(B) In the subtractive setting

$$T=\mp t\pm(m_1N_1-m_2N_2)\lambda/2, \tag{61}$$

$$dT/d\lambda=\pm(m_1N_1-m_2N_2)/2. \tag{62}$$

Substitution of Eqs. (44) and (62) into (46) yields

$$\frac{d\theta}{d\lambda}=-\frac{\cot\theta}{\lambda}-\frac{(m_1N_1-m_2N_2)\cot\theta}{2[t+(m_1N_1-m_2N_2)\lambda/2]}. \tag{63}$$

The peculiarities of the dispersion can be conveniently seen from the graph (Fig. 1), in which the dispersion is shown plotted as a function of t, the value of $(m_1N_1+m_2N_2)\lambda/2$ being kept constant and equal to 2.4 centimeters. In the Michelson adjustment the dispersion is independent of t; the minus sign indicates that an increase in λ is accompanied by a decrease in θ. In the chromatic adjustment the dispersion becomes very large when t has the value of $(m_1N_1+m_2N_2)\lambda/2$. In the complementary adjustment the dispersion is zero when t equals zero; however, for small values of t the dispersion becomes very large except for identical gratings in which case it is the same as for the Michelson adjustment. In all cases the dispersion approaches that of the Michelson instrument for very large values of t. The values of the dispersion in the complementary and chromatic setting have been plotted only for the subtractive settings.

Optics in the Classroom

Apparatus for Experiment on Absorption of Light by Sodium Vapor

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THIS paper describes apparatus and procedure intended primarily for classroom study of the principal series line absorption spectrum of sodium vapor,[1, 2] as shown in Fig. 1. The design of the equipment and the suggestions relative to operating it represent the result of extended development in which safety has had first consideration. The experiment has been in use for a decade and as many as twelve three-hour performances are made during the school year.

The absorption tube is constructed of seamless "18–8" stainless steel. The ends are connected by small stainless steel tubes to water-cooled chambers provided with cemented fused silica windows which are kept clear by slow streams of dry nitrogen. The total pressure is atmospheric or slightly above at all times and hence a vacuum pump is not required and the joints need not be perfectly tight. The construction is not difficult and the cost is low.

One form of absorption tube which has proved to be satisfactory is illustrated in Fig. 2. The dimensions are not critical although to prevent excessive heat transfer to the water-cooled chambers the connecting tubes should have thin walls. Asbestos paper serves as electrical insulation between the steel and a No. 22 nickel-chromium wire winding whose resistance is approximately 20 ohms. The turns are concentrated near the ends to insure nearly uniform temperature along the length of the absorption tube. A second heater may be placed around the side tube but this is not essential. A Chromel-Alumel thermocouple junction pressed firmly against the steel provides means for estimating the temperature. The tube and thermal insulating material, such as Babcock and Wilcox K26 firebrick cut to shape, are housed in a sheet iron box with the water-cooled chambers and side tube projecting outside.

The nitrogen is obtained from a tank of compressed gas through a needle reducing valve. Only dry, practically oxygen-free gas is used. The use of any kind of drying equipment is to be avoided. To insure equal pressures within the window chambers, a necessary condition for satisfactory operation, the inlets are connected in parallel through 0.8 mm capillary tubes about 30 cm long. The individual lengths required for equal flows are found initially by trial. The outlets are connected to a relatively large exhaust tube which leads directly to a ventilating hood or the equivalent.

The absorption tube should be perfectly dry and filled with nitrogen when it is loaded. Small, freshly cut pieces of sodium are inserted through the side tube with the aid of a ram rod, after which the tube is closed with a lead washer and screw cap. Dry sodium sealed in metal cans is recommended. It may be handled safely with metal tweezers and cut with a knife on a sheet of glass. Unused sodium is stored in a tightly closed new paint can from which most of the air may be displaced by nitrogen. A kerosene bath is not recommended because subsequent use requires washing. In general the vapors of oil solvents, which can safely come in contact with cold sodium, form explosive mixtures with air and thus add to the hazard. Moisture can appear from a number of unsuspected sources, including the solvent itself. Scraps of sodium should not be left lying on the table or dropped on the floor; fires could result long after they had been forgotten.

Dry sand should be conveniently accessible for use in case of fire. As is well known, liquid extinguishers are worse than useless when an alkali metal is involved.

In connecting the various gas lines it might be advisable from the standpoint of safety to use

[1] R. W. Wood, Astrophys. J. **29**, 97 (1909); *Physical Optics* (The Macmillan Company).
[2] G. R. Harrison, Proc. Nat. Acad. Sci. **8**, 260 (1922); Phys. Rev. **24**, 466 (1924); Phys. Rev. **25**, 768 (1925).

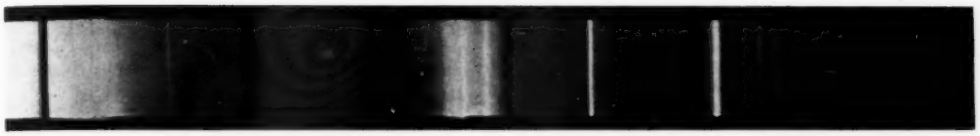

FIG. 1. Higher members of the principal series of sodium in absorption.

only strong metal tubing. It is customary, however, to use glass and rubber. All glass should be enclosed within metal. Rubber tubing, whether enclosed or not, should be clean. These precautions are indicated by anticipation of possible conditions differing markedly from those under which the experiment has been entirely satisfactory.

Cleaning is seldom necessary. If the side tube becomes clogged so that a fresh charge of sodium cannot be introduced easily, the ram rod is used to open it. The end constrictions may be cleared in a similar manner after removal of the windows. Sodium condensed in the water-cooled chambers ordinarily does no harm as long as the gas tubes remain fully open.

When not in use for any considerable length of time, as between semesters, the gas inlets and outlets are connected together by short lengths of dry rubber tubing. A cool, dry place is selected for storage.

In operation, the absorption tube is placed with its axis in careful alignment with a quartz-prism or grating spectrograph and a source of continuous visible and ultraviolet radiation. Ordinarily no lenses are used, a practically coherent mode of slit irradiation[3, 4] being employed. The heating current is controlled by a rheostat or variable voltage transformer. Although absorption may be studied at any vapor pressure up to one atmosphere, overheating is to be avoided. Interesting results are obtained when the temperature is in the neighborhood of 600°C, for example.

Of the numerous sources which are useful in spectral absorption experiments one of the most convenient is the quartz mercury arc operated at relatively high temperature, e.g., the Uviarc, or the H3 lamp, manufactured by the General

[3] P. H. van Cittert, Zeits. f. Physik **65**, 547 (1930).
[4] D. C. Stockbarger and L. Burns, J. Opt. Soc. Am. **23**, 379 (1933).

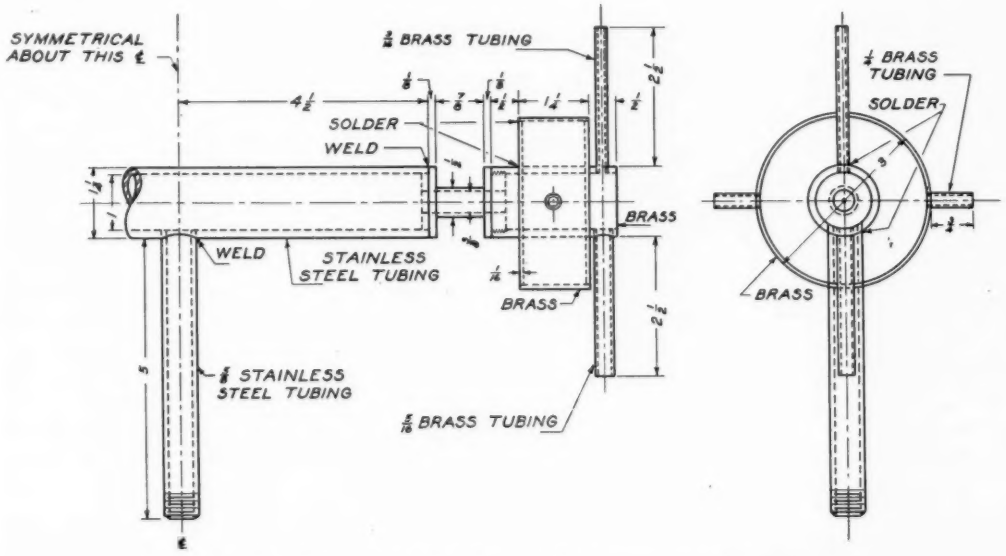

FIG. 2. Drawing of a recent model of the atmospheric pressure steel absorption tube.

Electric Vapor Lamp Company. The latter is unsuitable in its standard form. The fused silica capillary tube, which contains a small drop of mercury and a starting gas, has two small tungsten lead-in wires sealed with a single kind of glass instead of the more familiar graded glass-to-silica seal. Unlike the latter, the single glass seal deteriorates if the wire becomes oxidized, and for this reason the arc tube is enclosed in a glass (Nonex) envelope filled with a non-

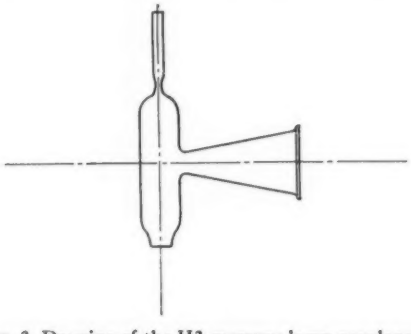

FIG. 3. Drawing of the H3 mercury lamp envelope with flanged window tube and exhaust tubulation attached. The funnel angle may be increased beyond that indicated.

oxidizing gas. Operation of the arc with a hole in the envelope[5] or with the glass entirely removed to permit passage of the shorter wave-length ultraviolet radiation is possible but experience has shown that it may result in a relatively short life. It is a simple matter to provide a window of fused quartz cemented to the flanged end of a side tube, as illustrated in Fig. 3. The tube should, of course, be long enough to keep the joint cool. The flange is ground practically plane with fine abrasive powder and water against a piece of plate glass, for example, and coated with a thin layer of General Electric Glyptal lacquer after cleaning thoroughly and drying. The window is pressed on firmly until it is in contact with the flange and the excess lacquer has been forced out. The resulting seal film should be free from bubbles and streaks of air. Drying of the joint requires several days.

It is unnecessary to take the lamp apart to add the side tube. A small flame directed at the top of the envelope produces a hole, a tubulation with seal-off constriction is attached and then an opening is blown in the side wall at a point opposite the arc tube. During these operations, and in adding the side tube, care is taken to prevent the flame from striking the arc tube and wires.

With the arc in operation, the envelope is exhausted for several hours, filled with nitrogen at atmospheric pressure and then sealed off.

For photographing an absorption spectrum on a pure continuous background an incandescent lamp with a quartz window[6] is useful. Originally assembled in a factory at relatively high cost, such lamps are now fabricated and exhausted in the laboratory so that their inherently short lives are of little concern. With Pyrex glass it is a simple matter to open the envelope neatly with a hot wire and reseal it after inserting a new filament. The graded Pyrex-to-silica joint is shorter and cheaper than the one required for soft glass bulbs. The filament is sometimes obtained by opening a small commercial projection or headlight lamp and cutting off the glass stem a little below the press. In this way the support wires are left intact. The filament assembly is attached to the lead wires of the Pyrex lamp by miniature double connectors or by welding. For long life at the highest temperatures solid filaments are better than coiled ones. A demountable lamp using a heavy strip of tungsten has recently been described.[7]

Apparently the number of principal series members of sodium which can be observed with the apparatus described is determined largely by the resolution of the optical system. With a mercury arc source, students obtain about 15 members with a small quartz spectrograph and 30 or more with a medium size instrument, as shown in Fig. 1.

Professor E. B. Millard and Mr. A. C. Melcher have contributed materially to the solution of safety problems. Dr. R. D. Mailey and Mr. L. B. Johnson of the General Electric Company have given valuable information relative to high pressure mercury vapor light sources. Mr. J. M. Kolligian took an active part in the construction and testing of the steel absorption tubes. To these and all others who aided in the project I express my gratitude.

[5] J. G. Winans, Rev. Sci. Inst. **9**, 203 (1938).

[6] D. C. Stockbarger, J. Opt. Soc. Am. and Rev. Sci. Inst. **9**, 337 (1924).

[7] H. Beutler and N. Metropolis, J. Opt. Soc. Am. **30**, 115 (1940).

Letter to the Editor*

Separation Negatives For Color Photography

Since it is now "time to stump the experts," may I point out the absolute dearth of quantitative technical information in the field of tri-color separation negative making in color photography?

When I want salt, I can go to the nearest chain store and buy a hat full for a nickel; or I can go to a chemical supply house and buy chemically pure sodium chloride with a complete chemical analysis. In the latter case I know what I'm working with. Filters and negative materials for color work are at present in the grocery store class; before using for quantitative work they must be "analyzed" and rejected or accepted before a balanced set of separations can be made. What I need for my color work are materials more nearly of the chemically pure variety with a quantitative statement of their characteristics. Let me give several specific instances of lack of technical information.

Filters.—Transmission characteristics for Wratten filters are published by Eastman, but nowhere can I find any mention of the tolerances within which actual filters may be expected to lie nor how close to the published specifications it is possible to secure individual filters. In consequence it is not surprising to find two No. 58 filters, one of which transmits 30 percent more light than the other. Filters are not interchangeable.

Filter factors.—Published filter factors are a waste of good white paper and ink, since they may be in error by several hundred percent. No information is available concerning the conditions under which these published factors are obtained nor whether or not they are intended for separation negative making. To be of any value, the color temperature and intensity of the light source should be stated and, if a nonreciprocity law material, whether the factors were determined by time scale or intensity scale exposures. Standard developing conditions should be stated and curves given where necessary for reciprocity failure factor variation.

Negative emulsions.—While emphasis is placed on the necessity for the use of an emulsion having straight line characteristics, no accurate information is available concerning this essential for a balanced set of separations. Most of the modern emulsions which I have tested give curved characteristics, no part of which may be considered straight; moreover the curvature varies as between the different tri-color filters in consequence of which exact superposition of the characteristics is impossible and yet necessary for color balance. Further, the developing agent used and method of development affect the curvature, yet no specific information is available to cover this important phase of the work. Some years ago, I think in November and December, 1938, Dr. MacAdam published in the Journal two communications on masking for wash-off relief color printing. He referred several times to the necessity of a straight line characteristic in his negative material, a "well-known panchromatic emulsion." Hamlet, with the melancholy Dane omitted.

Uniformity of emulsion coating is another factor which should have quantitative expression. About a year and a half ago a case of 5″×7″ Defender X F Pan cut film was scrapped because there was a variation of ±0.03 in density of a uniformly fogged specimen, machine developed to a gamma of 0.8 and an average density of 1.0, making it unusable for highlight color work.

Further, when a satisfactory combination of emulsion and developer have been found to give straight characteristics with a range of gamma suitable for use, it is no indication that successive batches of the same emulsion will be suitable. Eastman Super-Sensitive Panchromatic Safety Anti-Halation cut film, emulsion 6116-431 on 5/30/39, gave a No. 47 filter gamma of 0.81 with 10 minutes development; emulsion 6116-467 on 5/24/40 gave a gamma of only 0.67 under the same conditions; it was scrapped.

During the last two years I have spent months, literally, in the darkroom on essential yet nonproductive work securing data which I am sure the manufacturers already have and which I can't get in any other way.

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RR3, Newton, New Jersey,
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* Opinions expressed in "Letters to the Editor" are those of correspondents, and no responsibility for them is taken by the Journal.